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Spalling of fibre reinforced concrete under fire

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ABSTRACT

Fire exposure represents one of the most severe loading conditions for reinforced concrete structures, leading to severe physical and mechanical degradation. Among the most critical fire-induced phenomena is spalling, which may result in substantial material loss, reduction of the effective cross-section, and exposure of reinforcement, thereby compromising structural safety. Accurate quantification of spalling damage is therefore essential for reliable post-fire structural assessment.

This thesis focuses on an experimental assessment of fire-induced spalling in concrete specimens supplied by HINFRA and produced with different material compositions. Three concrete types were examined, including ordinary reinforced concrete, fibre-reinforced concrete, and concrete with inclusion of polypropylene (PP) fibres, with a total of ten specimens tested. The specimens were previously subjected to controlled furnace fire exposure, while the present study concentrates on post-fire analysis.

Particular attention is given to polypropylene fibres in minimizing the occurrence of explosive spalling. Due to their relatively low melting temperature, PP fibres melt during heating and create additional pore channels within the concrete matrix, enhancing permeability and reducing pore pressure buildup, therefore is expected to significantly decrease spalling severity compared to ordinary mixtures.

The experimental work combines three-dimensional surface scanning to measure maximum spalling depth and volume loss and compressive tests to measure residual strength. The report aims to compare the performance of the different concrete types in terms of spalling severity, with special emphasis on the performance of PP fibre-reinforced concrete under fire exposure. The results contribute to a deeper understanding of material composition in mitigating fire-induced damage in concrete structures.

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1 INTRODUCTION

Concrete is one of the most widely used construction materials in civil engineering due to its high compressive strength, durability, and non-combustible nature. Compared to other structural materials, concrete generally exhibits satisfactory performance when exposed to elevated temperatures. Nevertheless, due to its complex composition, fire represents one of the most severe loading conditions for concrete structures, as it can induce significant thermal, physical, and mechanical degradation.

It is widely recognized that exposure to elevated temperatures significantly alters the mechanical properties of concrete. These temperature-induced changes in concrete properties have been extensively documented in technical literature and professional guidelines, including reports from ACI 216R-89, CEB Bulletin d'Information No. 208, RILEM Committee 44-PHT, the CEN Eurocodes, and publications from the Concrete Reinforcing Steel Institute on reinforced concrete fire resistance[1].

Among the various fire induced deterioration mechanisms, spalling is considered one of the most critical phenomena. Spalling refers to the detachment or loss of concrete material from the surface of an element subjected to high temperatures, ranging from gradual surface flaking to violent explosive spalling. This phenomenon is one of the most detrimental effects causing damage or even failure of the concrete members during or after a fire by decreasing the residual mechanical properties and structure's durability. Particularly, a major hazard is explosive spalling, which can seriously compromise the fire safety of reinforced concrete structures. It takes place when thermally induced stresses, including compressive stresses and tensile stresses perpendicular to the heated surface, exceed the tensile capacity of the concrete, leading to the violent ejection of material fragments[2]. This process reduces the effective cross-section of the structural member and may leave the reinforcing steel directly exposed to fire.

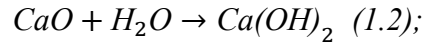
The irregular nature of this phenomenon and the inhomogeneity of the concrete structures are among the primary factors why the real mechanism of spalling is still poorly understood after numerous experimental and numerical research[3].

It is important to understand the physics governing this phenomenon in order to predict spalling and develop preventative measures. Spalling in concrete exposed to fire is generally the result of a complex combined action of pore pressure buildup due to moisture vaporization and thermally induced tensile stresses[4].

At elevated temperatures, concrete undergoes thermo-chemical decomposition that significantly affects its structural integrity. One key reaction is the decarbonation of calcium carbonate present in calcareous aggregates and hydrated cement paste:



This endothermic reaction produces calcium oxide (CaO) and releases carbon dioxide (CO₂) gas, contributing to increased internal pore pressure and microstructural weakening. During the cooling phase, calcium oxide may react with moisture according to:



This rehydration process forms calcium hydroxide and is accompanied by volumetric expansion, which can induce additional cracking. These irreversible chemical transformations alter the microstructure of concrete, reduce mechanical strength, and increase susceptibility to fire-induced spalling.

Pore pressure–induced spalling is primarily related to coupled thermo-hygral processes occurring within concrete exposed to high temperatures. As heat is transferred into the material, moisture migrates and vaporizes, leading to a progressive increase in pore pressure within the microstructure as seen in Fig. 1-1 [5]. Spalling, often explosive, takes place when the -tensile stresses generated by this internal pressure exceed the tensile capacity of the concrete.

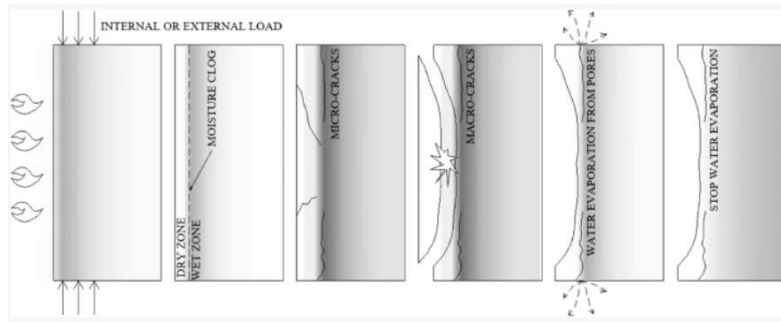


Figure 1-1[5]: Evolution of hydraulic processes in fire-exposed concrete.

Thermo-mechanical spalling mechanism refers to spalling occurrence due to stresses induced by high thermal gradient during sudden influx of heat. Due to thermal expansion of concrete temperature gradient results in formation of compressive stresses at the heated zone and tensile stresses in the colder regions [6]. Moreover, further in the paper it could be observed that high thermal gradient within some of the specimens was measured when subjected to standard ISO 834 heating rate.

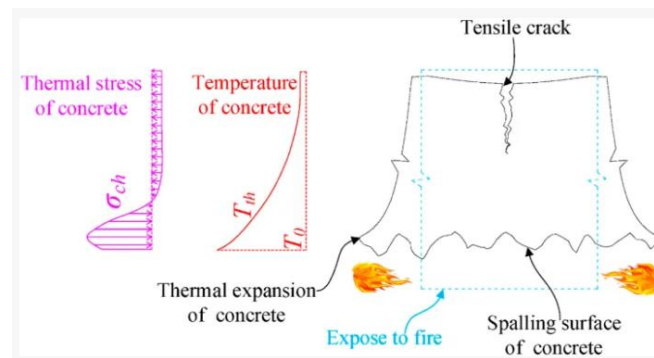


Figure 1-2[6]: Mechanism of concrete spalling due to thermal stress.

The state of the art reveals two main interpretations regarding thermal stress-related spalling. Some researchers attribute spalling to tensile stresses arising from steep temperature gradients within the concrete [7], [8], whereas others argue that it results from compressive stresses caused by restrained thermal expansion [9]. Phan and Corino [10] summarized that pore built up pressure might be the primary cause for fire induced spalling, while thermal stress induced

thermal gradient is secondary. Pore pressure build up is observed to be the governing mechanism for explosive spalling, confirmed by extensive research [4].

Recent studies also propose a theory that spalling occurs when combined effects of both thermal stresses and water vapor pressure induced stresses exceed that of the concrete tensile strength [6].

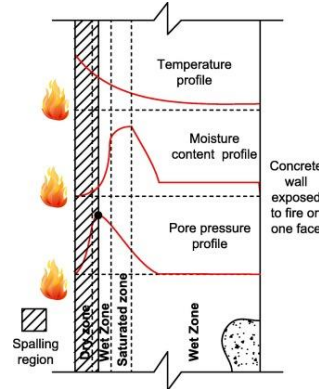


Figure 1-3[6]: Schematic representation of thermo-hygral spalling of a concrete wall exposed to fire on one face.

Several factors influence the occurrence and severity of spalling. The influencing factors could be generally summarized by following categories [6]:

- Material: properties related to mix design (i.e., permeability, w/c, moisture content, curing duration, aggregate type and size and etc.).
- Structural: factors associated to the function of concrete sample (i.e., column, beam, slab and etc.).
- Mechanical: factors related to presence/absence of applied loads and restraint conditions.
- Temperature: heating rate that the sample is exposed to.

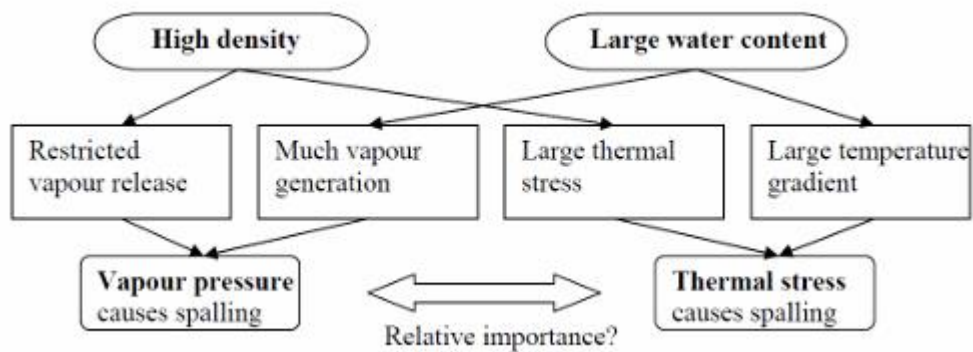


Figure 1-4[11]: Summary of factors to be included in the spalling analysis.

Permeability is one of the key factors mitigating spalling. Since moisture migration depends on the permeability, low permeability doesn't allow trapped vapor to migrate quickly, and leads to pore pressure build-up, which consequently results in explosive spalling. Therefore, some research on spalling focuses studying specifically the effects of fire on HSC (High Strength Concrete), as it has lower w/c ratio and lower permeability compared to NSC (Normal Strength Concrete).

Degree of pore saturation (DPS) is also one of the parameters used to predict the spalling risk. It was found that dense concrete is more susceptible to spalling, and as moisture content increases, the occurrence and severity of explosive spalling increases [12]. Eurocode 2 recommends to limit the moisture content to less than 3% by weight.

The type of aggregate used in concrete plays a significant role in its behaviour under fire exposure. Concrete produced with aggregates that contain little or no silica, such as limestone, basic igneous rocks, crushed brick, and blast-furnace slag, generally exhibits a smaller reduction in strength at elevated temperatures. In particular, dolomitic limestone can enhance fire resistance because the calcination process absorbs a portion of the heat, while the resulting lower-density calcined material improves the thermal insulation capacity of the concrete[1].

Although HSC has better overall structural performance compared to NSC, susceptibility to spalling, due to low permeability, remains its biggest disadvantage. Widely accepted solution to considerably reduce occurrence and intensity of fire induced spalling is shown to be inclusion of polypropylene (PP) fibres in concrete mix. For instance, Eurocode [13] recommends including at least 2 kg of monofilament PP fibres per cubic meter concrete for high-strength (>55 MPa cube compressive strength), high moisture content (>3% by mass) and/or concrete with high inclusion of silica fume (>6% by mass of cement).

In the near past, there has been an increase in implementation of fibre reinforced concrete (FRC), due to its improved mechanical properties such as higher tensile strength, higher resistance to cracks and fractures and higher energy absorption. Fibers can be classified in two categories based on their performance under fire [14]. For instance, steel, carbon and basalt fibres provide general mechanical improvement, enhanced heat stability and crack initiation resistance because of bridging effect. While PP fibres, due to their low melting point, create higher permeability which significantly reduce occurrence of explosive spalling.

Despite the fact that the inclusion of PP fibres in concrete mix design has been shown to be considerably effective against spalling for decades (i.e., [15],[16], [17]), there appears to be a debate and doubt on exact mechanism behind the efficacy. There are two widely mentioned possible mechanisms, ultimately, the idea behind them being improvement of moisture migration.

Volumetric changes in fibres during fire could results in formation of microcracks in the concrete matrix (discontinuous reservoirs), thus facilitating moisture migration. Moreover, it is also theorized that as the temperature keeps rising, polypropylene fibres eventually melt, thus leaving behind vacant channels and enhancing moisture transport [18].

In addition to modifying the concrete composition to improve fire resistance, external passive fire protection systems can also be applied to structural elements. Passive fire protection aims to delay heat transfer to structural components and maintain their load-bearing capacity during fire exposure. Such systems include thermal insulation barriers, mineral-based fireproof coatings, intumescent materials, and ablative protective layers. These materials are often applied directly to structural elements to form an insulating barrier that slows the temperature rise within the structure. Mineral-based fire protection materials frequently incorporate aggregates such as vermiculite, which provide low thermal conductivity and enhance thermal resistance under fire conditions[19].

Despite extensive research on fire-induced spalling, uncertainties remain regarding the influence of fibre combinations and moisture conditions on residual thickness and damage patterns.

To contribute to a better understanding of the behaviour of concrete subjected to fire exposure, the following specific objectives were established for this research:

1. To investigate the spalling behaviour of concrete specimens exposed to high temperatures, with particular attention to the influence of different concrete compositions, including ordinary reinforced concrete (ARM), fibre-reinforced concrete (FRC), and polypropylene fibre modified concrete (PP).
2. To analyse the temperature development within the concrete specimens during fire exposure using embedded thermocouples placed at different depths, in order to evaluate the thermal penetration and its relation to damage development.
3. To quantify the geometrical characteristics of fire-induced damage, including maximum spalling depth, remaining thickness, and volume loss, through post-fire assessment using three-dimensional scanning techniques.
4. To evaluate the residual mechanical performance of fire-exposed concrete by conducting compressive strength tests on core samples extracted from the specimens after fire exposure.

To achieve the first and second objectives, the results obtained during the fire tests were analysed, focusing on the evolution of internal temperatures recorded by the thermocouples and the visual damage observed after exposure.

The third objective was addressed through detailed geometric analysis of the specimens after testing. Three-dimensional scans of the exposed surfaces were processed to determine the extent and distribution of spalling damage. Parameters such as maximum spalling depth, remaining thickness, and volume loss were calculated to compare the performance of the different concrete mixtures.

Finally, to assess the residual mechanical properties of the fire-exposed material, compressive tests were carried out on core cylinders extracted from the specimens. The results were used to evaluate the degradation of compressive strength and to provide further insight into the structural implications of fire-induced damage.

This thesis is organized into five chapters. Chapter 1 presents the background of the study, discusses the current state of knowledge on fire-induced spalling in concrete structures, and defines the research objectives. Chapter 2 reviews experimental methodologies reported in the literature for the assessment of fire-induced spalling, including fire exposure conditions, testing configurations, and post-fire evaluation techniques. Chapter 3 describes the experimental program conducted in this study, including the fire testing procedure, post-fire geometric analysis, and compressive testing of extracted cores. Chapter 4 presents and analyses the results obtained from the experimental campaign. Finally, Chapter 5 summarizes the main findings of the research and discusses the implications of the results.

2 REVIEW OF SPALLING TESTING METHODOLOGIES

Fire-induced spalling of concrete has been extensively investigated through a wide range of experimental methodologies. The conventional approach to assess the sensitivity of concrete to explosive spalling involves exposing specimens or structural elements to fire conditions within a furnace and subsequently quantifying either the volume or the depth of detached material. In some cases, in-situ fire testing is also performed to evaluate spalling behaviour under realistic conditions. However, despite the extensive experimental tests conducted, the results appear to be scattered as critical parameters in testing procedures vary in some degree due to absence of standardized procedure. For instance, parameters such as concrete composition (i.e., moisture content, aggregate type and size, fibre dosage, amount of cement, permeability and etc.), curing conditions, dimensions, restraint and loading conditions tend to vary. These methodologies differ in scale, boundary conditions, loading configuration and measurement techniques.

In general, spalling tests can be classified into material screening tests and large-scale fire resistance tests. The following section provides a structured overview of the main experimental approaches adopted in the literature, with particular reference to the recommendations of RILEM TC 256-SPF [20].

2.1 FIRE EXPOSURE CONDITIONS

Fire exposure represents one of the most critical parameters in experimental investigations on concrete spalling, as the heating rate directly influences temperature gradients, pore pressure development, and thermo-mechanical stresses within the material. For this reason, standardized fire curves are typically adopted to ensure repeatability and comparability of results. Time-temperature curves of interest are presented in figure below [21]:

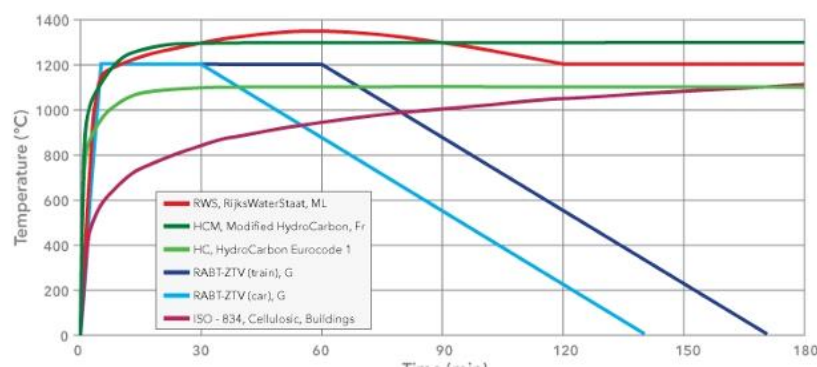


Figure 2-1 [21]: Time-temperature curves.

2.1.1 ISO 834 standard curve

The most commonly used fire curve in building fire resistance testing is the ISO 834 standard fire curve. It describes the temperature evolution inside a furnace as a function of time and is defined by the following equation:

$$T = T_0 + 345 * \log_{10} (8t + 1) \quad (2.1)$$

where:

- T is the furnace temperature (°C)
- T_0 is the ambient temperature, equal to 20°C;
- t is time (minutes)

Table 2-1[18]: Time-temperature data on ISO Standard Fire Curve.

Time, t	Furnace Temperature Rise $T-T_0$	Time, t	Furnace Temperature Rise $T-T_0$
min	°C	min	°C
5	556	90	986
10	659	120	1029
15	718	180	1090
30	821	240	1133
60	925	360	1193

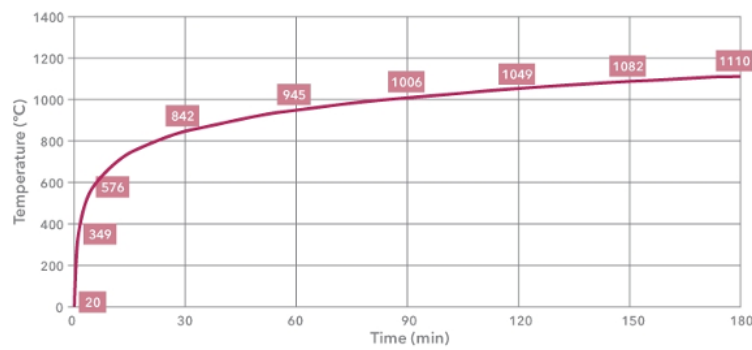


Figure 2-2 [21]:ISO 834 curve.

The curve produces significant thermal gradients across the specimen thickness, which can induce high pore pressure and internal stresses, contributing to fire spalling.

2.1.2 Hydrocarbon (HC) fire curve

Although the ISO curve has been one of the most widely used over the years, it has been found that the combustion rates of some materials, such as those produced in the petrochemical industry, far exceed those predicted by the curve described above. The hydrocarbon curve is applicable where small oil fires could occur, such as in car fuel tanks, oil tankers or some chemical tanks.

The temperature development of the hydrocarbon (HC) fire curve is described by the following equation:

$$T = T_0 + 1080 (1 - 0.325 e^{(-0.167t)} - 0.675 e^{(-2.5t)}) \quad (2.2)$$

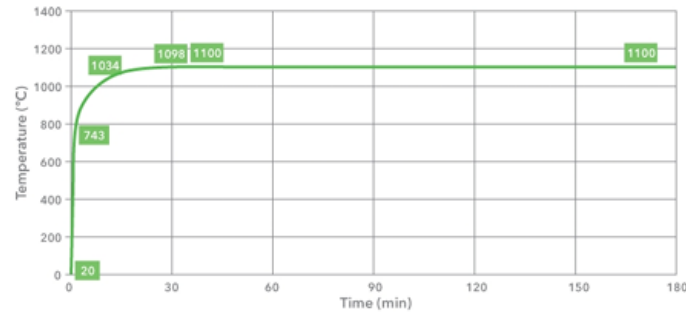


Figure 2-3[21]:Hydrocarbon curve (HC).

HC curve is characterized by rapid temperature increase, reaches: around 900°C in 5 minutes. Due to the very steep initial heating rate, the HC curve generates severe thermal gradients and higher pore pressure build-up compared to the ISO curve, thus increasing the likelihood of explosive spalling.

The heating rate plays a critical role in the spalling mechanism. Rapid temperature increases lead to:

- accelerated evaporation of pore water;
- limited time for moisture migration;
- sharp pore pressure build-up in the near-surface region;
- increased thermo-mechanical restraint stresses.

Consequently, more aggressive fire curves generally result in a higher spalling propensity, particularly in dense or high-strength concretes with low permeability.

In the present study, specimens were exposed to the ISO 834 fire curve in order to ensure consistency with standard fire resistance testing procedures and facilitate comparison with existing literature.

2.1.3 Other common fire curves

In addition to the ISO 834 and Hydrocarbon (HC) fire curves, several other temperatures–time curves have been developed to represent more severe fire scenarios, particularly in tunnel environments. One example is the Modified Hydrocarbon Curve (HCM) adopted in French regulations. This curve is derived from the hydrocarbon fire curve but assumes a higher maximum temperature of approximately 1300 °C, compared to 1100 °C in the standard HC curve. The steeper temperature increase during the first minutes of the HCM fire represents the rapid thermal conditions associated with fuel-based fires, which may induce severe thermal shock and increase the risk of explosive spalling in concrete structures.

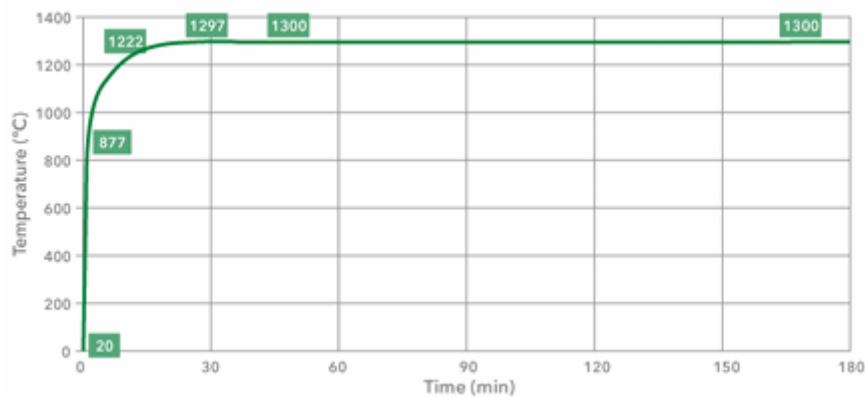


Figure 2-4: Modified Hydrocarbon Curve (HCM).

Another widely used tunnel fire scenario is represented by the RABT-ZTV curves, developed in Germany. These curves simulate fires caused by vehicles or trains in tunnels and are characterized by a very rapid temperature rise, reaching approximately 1200 °C within 5 minutes. Unlike the ISO or HC curves, the RABT curves include a cooling phase, where the temperature gradually decreases after a specified duration of peak exposure. Such temperature histories are intended to reproduce the development and subsequent suppression of tunnel fires.

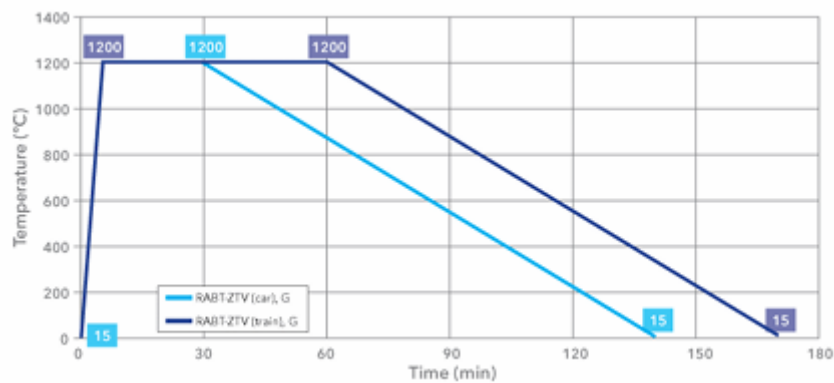


Figure 2-5: RABT-ZTV curves.

Table 2-2 provides an overview of design fire curves commonly used to represent different fire exposure scenarios.

Table 2-2: Overview of design fire curves and corresponding exposure conditions

Curve	Max Temp	Time to reach peak	Typical application
ISO 834	~1100°C	gradual	buildings
HC	~1100°C	5–10 min	petrochemical
HCM	~1300°C	very rapid	tunnels
RABT	~1200°C	5 min	tunnel vehicle fires

2.2 MATERIAL SCREENING TEST

Both in real fire scenarios and in standardized fire resistance tests, fire-induced spalling significantly affects the overall fire resistance of structural elements. Nevertheless, due to practical and economic constraints, simplified screening tests are required to optimize concrete mixtures prior to conducting full-scale element fire resistance testing. Given the numerous parameters influencing fire spalling in concrete, the guidelines for material screening tests are proposed by The RILEM Technical Committee 256-SPF to ensure a consistent and scientifically sound testing methodology.

Product screening tests are implemented when it is important to determine the fire resistance of a specific element (i.e., beam, slab, column and etc.), while material screening tests (small/medium scale) are generally useful when there is no information on the end use of material. The aim of the test being to conduct an experimental testing of different mixes with varied parameters (i.e., dosage, cement, fibre type, w/c ratio and etc.) to compare the behaviour of each mix.

The RILEM recommends to verify the severity of temperature and boundary conditions during the tests, as if those parameters are not adjusted properly, this could show no spalling which doesn't reflect the real fire conditions.

According to the guidelines [20], specimens should be square, round or rectangular shape and square and rectangular specimens should respect following dimensions:

- min. length of the fire exposed area sides a : 0.40 m;
- min. slab thickness D : 0.30 m—when the slab is tested unloaded;
- min. slab thickness D : 0.20 m—in case of restrained samples;
- min. slab thickness D : 0.15 m—in case of applied load;
- min. length of element sides L : 0.50 m.

The tested specimens satisfy all requirements defined for material screening tests according to the RILEM TC 256-SPF recommendation, with the exception of the minimum side length. The specimen side length was 0.48 m, which is slightly below the recommended minimum value of 0.50 m. Considering the marginal deviation and the overall experimental configuration, the testing campaign can be classified within the material screening framework throughout this study.

As mentioned before, often it is informative to measure the moisture content of the specimens. According to RILEM TC 256-SPF recommendations, the moisture content of concrete specimens should be determined as close as possible to the fire testing date, as moisture gradients within the cross-section significantly influence spalling behaviour. It is recommended to assess both near-surface moisture (within the first 5 cm) and internal moisture conditions. Moisture content is typically determined by oven-drying samples at $(105 \pm 5)^\circ\text{C}$ until mass equilibrium is reached [20]. In the case of the present study, although the specimens were tested after more than eight months of curing, which suggests a stabilized moisture state, no direct measurement of moisture content was conducted.

2.2.1 Mechanical boundary conditions

According to RILEM recommendations, regarding the mechanical boundary conditions, the following categories of tests are defined:

- (a) with no external mechanical load;
- (b) with external in-plane compressive loading using: (i) a post-tension system; (ii) a steel frame and lateral hydraulic jacks or other;
- (c) with restraint to thermal dilation of concrete element using (i) a steel ring, (ii) continuous steel frame or (iii) unexposed concrete rim with steel reinforcement.

Tests on unloaded specimens

The specimen is positioned horizontally on top of the furnace and subjected only to its self-weight, without any additional externally applied load. Temperature within the slab is monitored using thermocouples embedded during casting with different depth, while furnace temperature is measured using a flat thermocouple. This testing approach has been adopted in this study.

In laboratory investigations of concrete spalling, specimens are often designed to ensure controlled one-sided heating. For example, Malik et al. used prismatic specimens with a thermally exposed surface of 400×200 mm, while the ends were insulated to maintain cold boundary conditions and prevent excessive heat losses.

Tests on externally loaded specimens

In real fire scenarios, concrete structural elements are always subjected to load or restraint conditions[22]. Most research (i.e., [23],[24]) have shown that the presence of compressive stress during heating considerably increases both the internal compressive stresses and the pore pressure within the concrete, thereby elevating the likelihood of fire-induced spalling. However, other studies ([25], [26]) found that higher levels of load could actually reduce the occurrence of spalling. It has been suggested that loading intensity plays a significant role, as increased load levels can generate microcracking within the concrete, facilitating vapor escape and thereby potentially decreasing the risk of spalling. Nevertheless, although numerous investigations have examined the influence of mechanical loading on fire-induced spalling, its exact role and mechanisms are not yet fully understood. Therefore, the level of applied compressive stress is a critical parameter that must be considered when assessing spalling behaviour of concrete.

The compressive load could be applied using a post tensioning system, lateral hydraulic jack, and others systems that enable uniaxial or biaxial loading.

Uniaxial compressive loading: Post tensioning system

The experimental setup conducted by Heel and Kusterle [27] involves testing slabs with dimensions 1400 mm x 1800 mm x 300 under induced fire and loading conditions. Compressive stresses were applied by tensile stress in the tendons and was monitored by readout of prestressing force on the prestressing jacks to simulate structural conditions during fire. Temperature and pore pressure were monitored during heating by two thermocouples and monometer respectfully, and spalling behaviour was assessed both during and after the test. The setup aimed to reproduce real tunnel fire conditions and investigate the influence of sustained mechanical loading on fire-induced spalling.

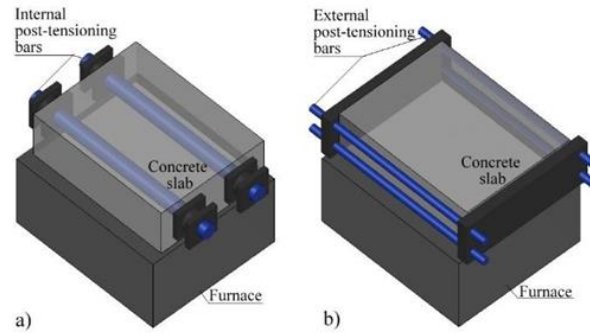


Figure 2-6 [28]: Testing sets in medium scale: a) with the inner post-tensioning bars, b) right with the outer post-tensioning bars.

Uniaxial compressive loading: Hydraulic jack

For smaller scale tests the application of hydraulic jack could be used to induce compressive stresses in relatively small specimens. Such tests were conducted at Université de Pau et des Pays de l'Adour in France [22] in a small mobile gas furnace , where concrete cube specimens (200 x 200 x 200 mm³) were placed in.



Figure 2-7[22]: Tested sample in the hydraulic press (left) and complete test setup (right).

The concrete specimens were heated according to ISO 834-1 fire curve, while at the same time being subjected to a constant uniaxial vertical compressive loading by the hydraulic jack. The specimens (cubes: 200 × 200 × 200 mm³ and prisms: 200 × 200 × 100 mm³) were positioned in front of the furnace between two high-strength polypropylene fibre-reinforced concrete cubes of identical dimensions to the cubic fire test specimens (see Figure 2-7, left). This arrangement was adopted to prevent a rapid temperature increase and to ensure uniform mechanical loading throughout the heating process.

To better understand the influence of compressive loading on the development and magnitude of pore pressure during the ISO 834-1 fire test, nine concrete cubes were prepared. The specimens were instrumented with four pressure sensors installed at depths of 10, 20, 30, and 50 mm from the exposed surface to enable simultaneous measurement of pore pressure and temperature during heating (see Figure 2-8).

- 16 radial cuts were introduced to reduce confinement from the colder rim.
- Spherical loading heads allowed rotation due to thermal curvature.

Seven stress levels were tested: 0, 0.5, 0.75, 1.5, 3, 5, and 10 MPa.

Tests were stopped after 30 minutes of fire exposure to compare spalling severity. However, collapse occurred in three slabs loaded at 5 and 10 MPa before 30 minutes.

The experimental tests confirmed that when concrete specimens are heated under biaxial compressive loading, cracks parallel to the loading direction tend to widen, while cracks perpendicular to the load tend to close, resulting in reduced permeability. Consequently, moisture cannot effectively escape from the critical spalling zone, leading to a rapid increase in pore pressure. The combined effect of elevated pore pressure and additional stresses (from restrained thermal strains and external loading) significantly increases the likelihood of fire spalling [30].

In contrast, when concrete is heated from the bottom surface under unloaded conditions, various cracks may develop, including orthogonal cracks in the core (perpendicular to the heated surface) and surface cracks parallel to the exposed face. These cracks can be beneficial, as they help relieve thermal stresses and pore pressure, thereby reducing the risk of spalling.

Test on specimens with restraint to thermal dilation

While externally loaded specimens are subjected to a controlled mechanical compressive force applied by external devices, whereas restrained specimens are not actively loaded but are prevented from expanding during heating, resulting in thermally induced internal stresses. This can be achieved by [20]:

- an external steel frame (Fig. 2-10. a);
- an unexposed concrete rim with steel reinforcement stirrup (Fig. 2-11);
- a steel ring (Fig.2-10. b).

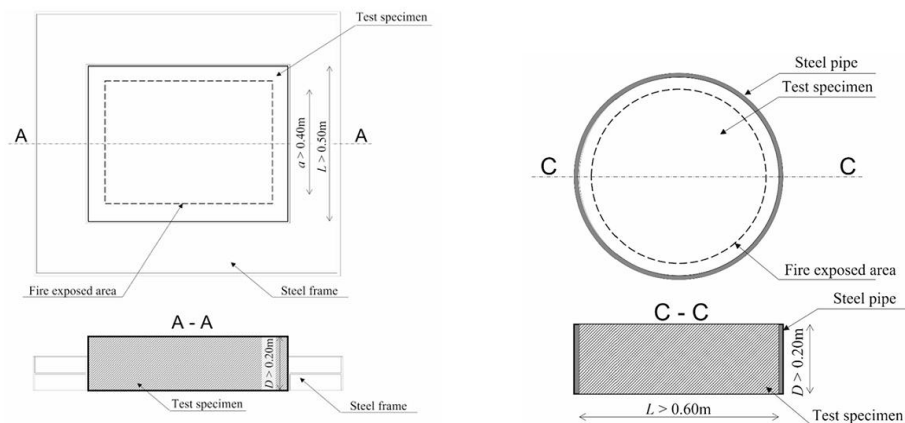


Figure 2-10[20]: a) External steel frame; b) a steel ring.

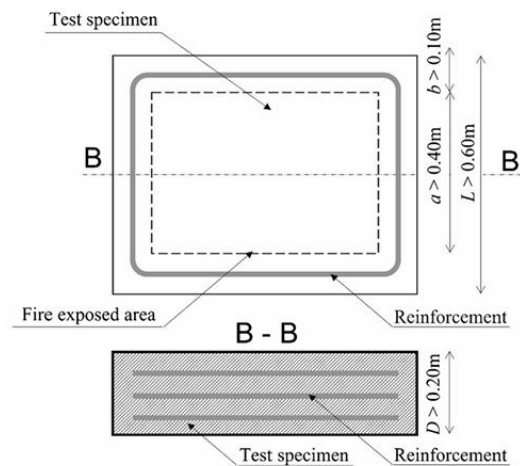


Figure 2-11[20]: Restraining concrete rim with steel reinforcement stirrup.

Carre et al [31] conducted a test on spalling effect with combining two type of loads. They tested specimens applying both restraint to thermal expansion and external compressive load. Six concrete slabs ($580 \times 680 \times 150 \text{ mm}^3$) were subjected to bottom-face heating over an area of $500 \times 600 \text{ mm}^2$ in accordance with the ISO 834-1 fire curve for two hours. Prior to heating, uniaxial compressive stresses of 0, 5, 10, and 15 MPa were applied using two flat jacks and maintained constant throughout the test. No spalling was observed in specimens loaded up to 10 MPa. However, significant spalling occurred in the slabs subjected to 15 MPa, indicating a critical loading threshold beyond which the risk of fire-induced spalling significantly increases.

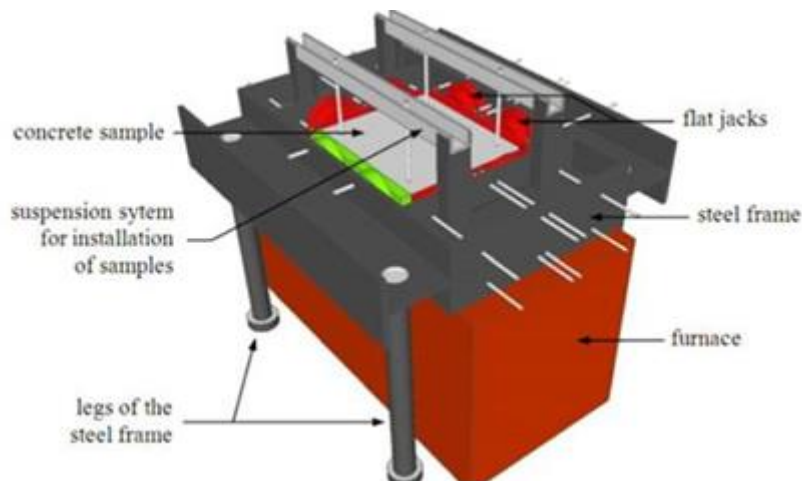


Figure 2-12[31]: Frame loading system.

2.3 LARGE SCALE FIRE TESTS

In full-scale experiments, the actual structural element is tested under restraint and loading conditions that closely replicate real service conditions. Primary aim the tests is to provide information about the fire resistance of the final products (beam, columns, tunnel linings). Such tests allow the evaluation of structural performance, temperature development within the element, and failure mechanisms under realistic fire conditions. Prior to conducting larger scale tests, it is recommended to set up material screening tests to optimize the material composition practically and economically.

2.3.1 Furnace types for full-scale fire resistance testing

Large-scale fire tests are commonly conducted in specialized furnaces designed to reproduce controlled fire exposure conditions. The configuration of the furnace depends on the type of structural element being tested. Horizontal furnaces are typically used for floor systems, slabs, and beams, where the specimen is placed over the furnace and exposed to fire from below. Vertical furnaces are commonly employed for testing columns subjected to one-sided fire exposure. In addition to these configurations, large-scale structural furnaces allow testing of full structural elements under combined thermal and mechanical loading conditions. In such setups, structural members span across the furnace opening while mechanical loads are applied using external loading frames in order to simulate realistic service conditions during fire exposure [32].

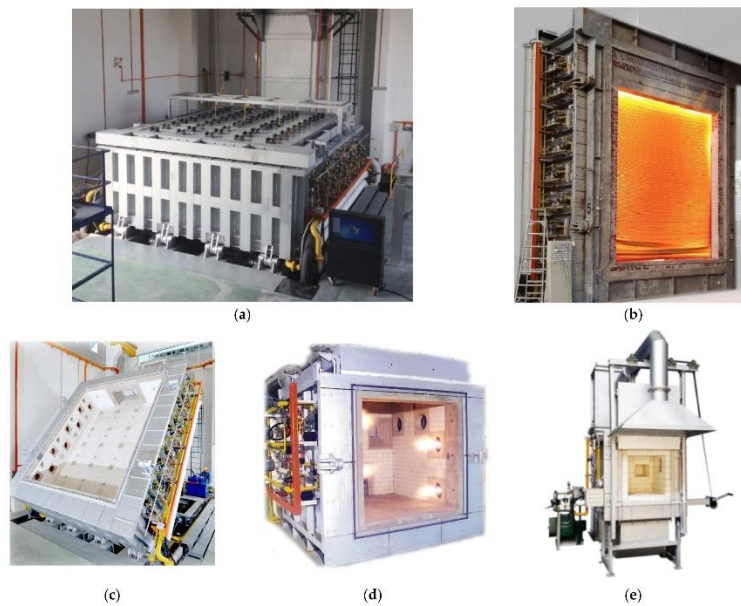


Figure 2-13[32]: Test furnaces: (a) horizontal, (b) vertical, (c) hydraulic, (d) indicative, and (e) miniature.

2.3.2 Boundary conditions in structural fire testing

In structural fire testing, boundary conditions and restraint conditions play a significant role in the behaviour of structural elements exposed to elevated temperatures. Structural elements are subjected to controlled heating in furnaces following prescribed fire curves such as ISO 834 or BS 476. Mechanical loads may be applied using hydraulic systems in order to simulate service conditions during fire exposure. The specimen support system must provide sufficient stiffness and rigidity to restrain the boundaries while allowing thermal deformation of the structural element. Internal temperatures are typically monitored using thermocouples embedded within the specimen.

Typical restraint conditions and loading arrangements used in standardized fire resistance tests for columns and beams are illustrated in Figures 2-14 and 15, respectively[32].

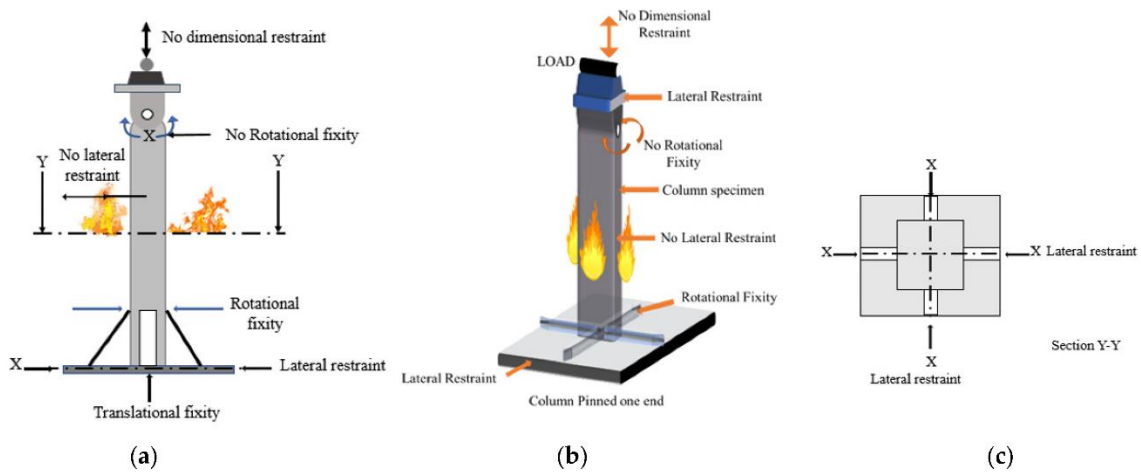


Figure 2-14[32]: Restraints for columns pinned at one end: (a) 2D, (b) 3D, and (c) section.

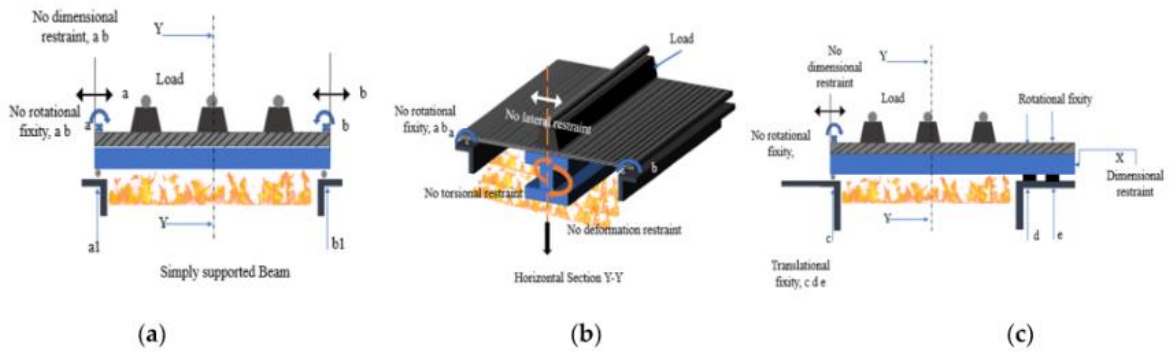


Figure 2-15[32]: Restraints for beams: (a) 2D, (b) section, and (c) beam fixed at one end.

2.3.3 Full-scale test on concrete wall or slab elements

Large-scale fire tests are often conducted on wall or slab elements exposed to standard furnace conditions in order to study thermal cracking and spalling behaviour under realistic boundary conditions. For example, full-scale tests on concrete wall elements of $1200 \times 1200 \times 300$ mm exposed to standard fire from both sides have been performed to investigate the development of thermal stresses in unloaded structural elements. In these experiments, the specimens were placed in the centre of a furnace while the edges were thermally insulated. Although explosive spalling was not observed, significant cracking developed through the thickness of the wall, demonstrating the role of thermal gradients and restrained expansion in crack formation[33].



Figure 2-16[33]: Testing set-up for concrete wall elements.

The authors explained this by the development of tensile stresses in the cooler core due to thermal expansion of the heated outer layers. Once cracking occurred in the wall interior, the compressive stresses near the heated surface were relieved, reducing the likelihood of explosive spalling. This study highlights that in large-scale unloaded wall elements, thermal cracking may become the dominant damage mechanism instead of spalling[33].

2.3.4 Full-scale tests on tunnel linings

Full-scale tests are especially important to conduct on tunnel linings, as fire in tunnels can generate extremely high temperatures and rapid heating rates that may cause severe spalling, loss of structural capacity, and potentially catastrophic failure. The test on tunnel lining segment was conducted at the Leipzig Institute [34].

A tunnel lining segment (3.43 m long, 1.80 m wide, and 0.55 m thick) was subjected to vertical loading at three points and horizontal loading in one direction using hydraulic jacks, as illustrated in Fig.2-17.

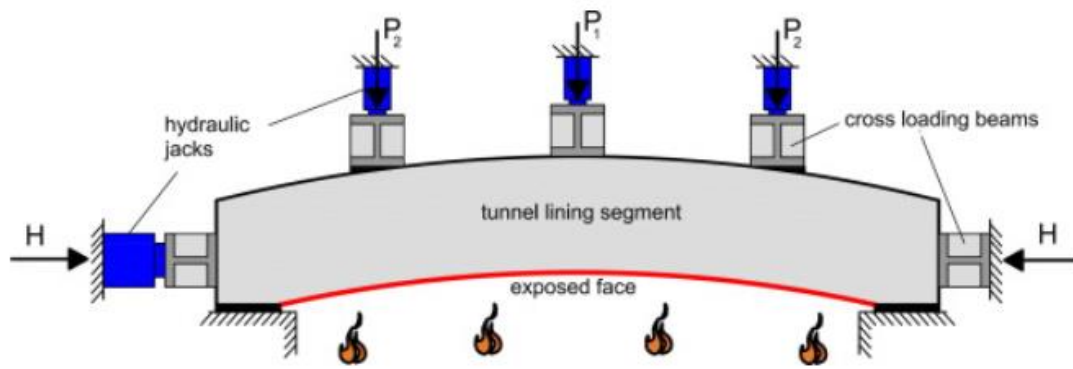


Figure 2-17 [34]: Full-scale fire test on tunnel lining segment.

The load was applied prior to heating and maintained constant throughout the test. Fire exposure was introduced at the bottom surface following the RWS (Rijkswaterstaat) fire curve.

During heating, both horizontal and vertical displacements at the actuators are continuously monitored, along with temperature variations through the thickness of the specimen. However, due to the significant time and cost involved, this type of experimental procedure is not suitable for screening multiple concrete mixtures. Instead, it is primarily intended for the final validation of a selected concrete under restraint, loading, and heating conditions that closely replicate real structural scenarios.

To address this limitation, the availability of a large-scale furnace allows multiple small slabs to be tested simultaneously. This approach enables the evaluation of different concrete mixes or specimen dimensions within a single fire test [28].

2.4 INSTRUMENTATION AND POST-FIRE ASSESSMENT

2.4.1 Measurements and observation before and during the test

There are some guidelines to consider before, during the test. Material properties such as mix proportions, aggregate type and size, presence of fibres and other physical and/or mechanical properties that are relevant to the study should be reported. Since the spalling phenomenon is strongly influenced by moisture content, it might be interesting to measure it prior to the test (close to the testing date).

During the test, it is useful to make following observations:

- Visual and acoustic monitoring of spalling, including the recording of the onset and times, as well as the characterization of spalling type (localized, generalized, or corner spalling), flake dimensions, and severity;
- Time of first spall and spalling duration until no spalling occurs, if applicable (min);
- The time at which reinforcement bars at various depths become exposed as a result of spalling should also be documented.

Conventional spalling tests typically rely on post-test evaluation of the damage. While temperatures inside the furnace and within the specimen can be measured during fire exposure, parameters describing the severity of spalling are generally quantified after the test. However, certain experimental techniques allow the monitoring of spalling propensity during heating. For example, Acoustic Emission (AE) methods, such as those conducted by Huismann et al. [35], characterize spalling by recording and counting acoustic events generated during the test. AE testing is a real-time monitoring technique in which sensors attached to the specimen detect high-frequency stress waves produced by internal cracking and material detachment under fire exposure. This approach enables identification of the onset, frequency and intensity of damage events. Nevertheless, it does not directly provide quantitative measurements of spalling depth or material loss.

During the test conducted by Huismann et al. [35], pressure gauge and sensors were also installed in order to measure the pore pressure within the specimen during the heating process.

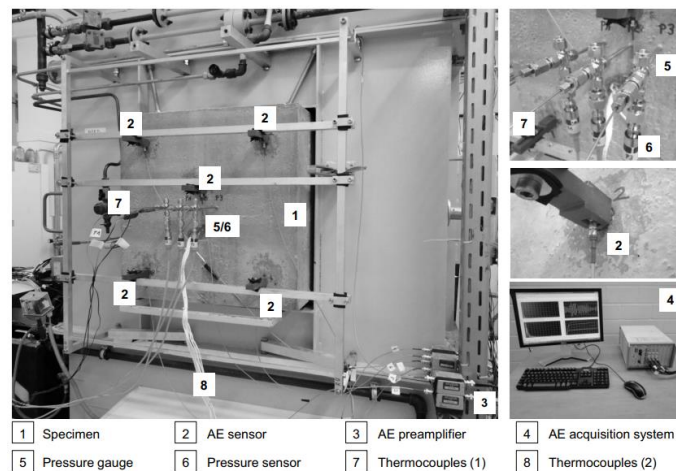


Figure 2-18 [35]: Test setup.

Another example of experimental set up mentioned in Chapter 2.2.1 by Politecnico di Milano [29] where temperature and pressure was measured during the test. Moreover, the flexural response was monitored using six Linear Variable Displacement Transducers (LVDTs), installed along the central axis and one edge of the slab, to record out-of-plane displacements at the unexposed (cold) surface as illustrated below.

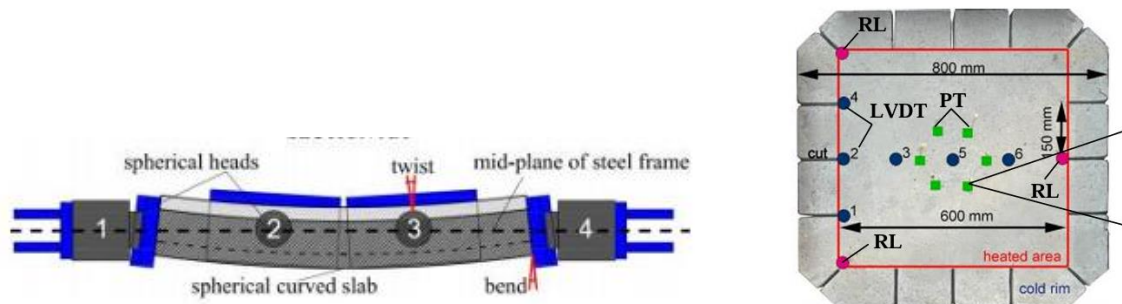


Figure 2-19 [29]: Deformed configuration (left); LVDT, pressure and temperature sensors placement (right).

2.4.2 Measurements after the test

The post fire examination consists of the evaluation of spalling depths. RILEM TC 256-SPF suggests that from the collected data, the following information shall be provided:

- Area of the spalled surface (spalled area);
- Mean spalling depth in the assessment area;
- Mean spalling depth in the spalled area (if spalling does not cover the whole assessment area);
- Maximum spalling depth (even if the maximum spalling point is out of the regular grid).

The measurements of spalling depths maybe performed manually in a regular grid in at least 20 evenly distributed points, or by using other means, e.g., 3D scanning or digital planimetry to collect data enabling drawing of a spalling map. Some post-test measurements are performed by the thickness profile of the spalled area was measured at room temperature by using a laser profilometer[29].

Spalling depth measurements may be carried out manually using a predefined measurement grid. The mesh spacing should be selected to ensure adequate representation of both the average spalling depth and the overall spalling profile. A minimum of 100 measurement points distributed across all heated surfaces of the specimen is recommended. In cases of localized spalling, the density of measurement points should be increased within the damaged regions. Additional measurement points may also be necessary for specimens with complex geometries.

For very large specimens, a maximum grid spacing of 50 cm is advised. In slender elements, such as columns or beams, at least three measurement lines per direction should be provided on each exposed face. Measurement points located near the edges of a heated surface should be positioned at a distance equal to half the mesh spacing from the edge.

Alternatively, automated techniques such as 3D scanning or digital planimetry may be employed to map the spalling profile. The measurement accuracy of the devices used should be within ± 2 mm. Since spalling may be non-uniform across the surface, both the average spalling depth over the entire heated area and the average depth within individual spalled regions should be determined.



Figure 2-20[20]: Example of grid for spalling depth distribution analysis.

Post-fire assessment by laser profilometry is a non-contact measurement technique used to quantify surface damage and spalling depth in fire-exposed concrete specimens. A laser beam is projected onto the damaged surface, and the reflected signal is used to reconstruct the surface height profile with high precision. By scanning across the spalled region, a detailed thickness profile is obtained (2D or 3D), allowing determination of mean and maximum spalling depths as well as estimation of volume loss. This method provides accurate geometric characterization of post-fire surface damage.

In this paper, post-fire assessment was performed by a 3D laser scanner and post processed using a software to quantify maximum and mean spalling depth and volume loss due to fire.

2.5 RECENT DEVELOPMENTS IN SPALLING ASSESSMENT AND PREDICTION

In recent years, the assessment of fire-induced spalling has progressively expanded beyond conventional experimental observation and post-fire mechanical testing toward hybrid frameworks that combine experiments, data-driven prediction, and advanced numerical modelling. A recent study by Moradi et al. [36] investigated the performance of fibre-reinforced concrete exposed to elevated temperatures using both experimental testing and a soft-computing approach. Their results confirmed the superior performance of polypropylene fibres over steel fibres in mitigating spalling under the investigated conditions, and the collected dataset was subsequently used to train a Group Method of Data Handling (GMDH) model for predicting relative compressive strength. The proposed model showed good agreement with experimental results, with a reported mean squared error of 0.0044, highlighting the potential of machine-learning tools to support the interpretation of complex high-temperature concrete behaviour. At the same time, the authors noted that such models remain limited by the availability of high-quality, comprehensive datasets and by the large number of interacting variables affecting concrete response under fire exposure.

A further development is represented by neural-network-based constitutive modelling, in which machine learning is used not simply to estimate a residual property, but to reproduce the full stress-strain response of concrete at elevated temperatures for structural fire analysis. In 2025, Wang et al. [37] proposed a transfer-learning framework in which a base neural network was adapted to different concrete datasets using a physics-informed custom loss function. The approach was specifically designed to improve predictions under limited data availability and to enforce physically realistic behaviour, such as zero stress at zero strain and monotonic stress-strain evolution around the peak response. The authors reported that the target model reduced prediction errors compared with both the base model and a conventional loss formulation, while also improving generalisation at unseen temperatures. The developed constitutive model was then implemented in a finite element analysis of a tunnel lining under fire exposure, where it was able to capture concrete degradation, stress redistribution, and their influence on structural displacement response during heating. These developments illustrate how recent predictive methods are moving from empirical strength estimation toward physics-informed modelling of structural response in fire scenarios.

Moreover, recent research has increasingly explored advanced machine learning (ML) and artificial intelligence (AI) techniques to improve the assessment and prediction of fire-induced damage in concrete. In addition to predicting residual compressive strength [38],[39],[40], fire resistance of beam and columns [41], and bond degradation [42], recent studies have also applied data-driven methods to image-based spalling assessment[43]. These approaches show strong potential for identifying complex relationships between material composition, exposure conditions, and observed damage

These recent studies indicate that the current state of the art is shifting toward integrated approaches in which experimental evidence remains essential, but is increasingly complemented by machine learning, transfer learning, and physics-informed numerical modelling[44]. Such methods offer clear advantages for handling the large number of variables involved in fire-induced concrete degradation and for extending predictions to conditions that are difficult to investigate experimentally. Nevertheless, they do not replace physical testing. On the contrary, both studies underline that predictive accuracy still depends on experimentally validated datasets and realistic material input, particularly because fire-induced spalling remains governed by coupled thermal, hydraulic, and mechanical processes. Therefore, recent developments should be understood as complementary tools that enhance, rather than replace, experimental spalling assessment.

3 EXPERIMENTAL TEST CAMPAIGN

3.1 MATERIALS: MIX COMPOSITION

The specimens investigated in this study were produced by the company *HINFRA*, which supplied the concrete blocks after fire exposure. Three different concrete mixtures were considered, including one ordinary reinforced concrete and two fibre-reinforced concrete (FRC) mixtures.

The first mixture, denoted as *ARM*, represents conventional reinforced concrete. This mixture was produced with a water-to-cement ratio of 0.42 and contained 450 kg/m³ of cement, 380 kg/m³ of sand (0–4 mm), 640 kg/m³ of mixed sand, and 680 kg/m³ of coarse aggregate (4–14 mm). Polypropylene macrofibres with a length of 60 mm were incorporated at a dosage of 1.0 kg/m³.

Table 3-1: Mix composition of Ordinary Reinforced Concrete (*ARM*).

Ordinary reinforced concrete (<i>ARM</i>)	[kg/m ³]
Sieved sand (0–4 mm)	380
Mixed sand	640
Crushed aggregate (4–14 mm)	680
Cement	450
Polypropylene macrofibres (60 mm)	1

Water-to-cement ratio (w/c)	0.42
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Moreover, 4th *ARM* specimen was coated with a spray-applied fire resistive material SFRM (Type M-II), a vermiculite-based insulating layer designed to provide passive fire protection. Due to its low thermal conductivity and insulating properties, the thermal exposure of the concrete core may differ significantly from that of unprotected *ARM* specimens. Therefore, *ARM4* is treated separately in the analysis. Table 3-2 reports some of the physical parameters that were determined according to testing procedures specified by ASTM.

Table 3-2: Physical properties of the fire-protective coating (Type M-II) applied to specimen *ARM4*.

Density	704–768 kg/m ³
Compressive strength	3.79 MPa ($\approx$ 550 psi)
Thermal conductivity	0.164 W/m·K
Adhesion / cohesion	774 kPa
Combustibility	Non-combustible
Maximum strain	0.06 mm/mm
Air erosion resistance	0.000 g/m ²

In addition to the ordinary reinforced concrete, two high-performance steel fibre-reinforced concrete mixtures were investigated, denoted as *FRC* and *FRC + PP*. Both *FRC* mixtures were characterized by a lower water-to-cement ratio of 0.35 and contained 600 kg/m³ of cement, 725 kg/m³ of sieved sand (0–4 mm), and 840 kg/m³ of crushed aggregate (2–8 mm).

Steel fibres with a length of 35 mm were added at a dosage of 60 kg/m³ in both mixtures. The *FRC HINFRA* + *PP* mixture additionally incorporated 60mm polypropylene (PP) microfibers at a dosage of 1.5 kg/m³.

Table 3-3: Mix composition of Fiber Reinforced Concrete (*FRC HINFRA*).

Steel Fiber reinforced concrete (FRC)	[kg/m ³]
Sieved sand (0–4 mm)	725
Crushed aggregate (4–14 mm)	840
Cement	600
Steel fibres (35 mm)	60
Water-to-cement ratio (w/c)	0.35

Table 3-4: Mix composition of FRC with added polypropylene (PP) microfibers.

Steel and PP Fiber reinforced concrete (PP)	[kg/m ³]
Sieved sand (0–4 mm)	725
Crushed aggregate (4–14 mm)	840
Cement	600
Steel fibres (35 mm)	60
Micro-fibre PP	1.5
Water-to-cement ratio (w/c)	0.35

Steel-fiber-reinforced concrete (SFRC) is a composite material in which discrete steel fibres are randomly distributed within the cementitious matrix. The most commonly used fibre geometries include hooked-end, straight, corrugated, and milled fibres. Typical steel fibres used in concrete have lengths of approximately 20–40 mm, aspect ratios (length-to-diameter ratio) between 40 and 80, an elastic modulus of about 200 GPa, and tensile strengths in the range of 800–1300 MPa. The addition of these fibres enhances the tensile capacity, ductility, and crack-bridging ability of concrete, which improves its resistance to crack propagation and helps maintain structural integrity under mechanical and thermal loading conditions[45].

Polypropylene fibres used in concrete are commercially available in various types and dimensions, with the most common being monofilament, multifilament, and fibrillated fibres (see Fig. 3-1,2). Monofilament and multifilament fibres are produced through an extrusion process and typically have nominal diameters ranging from 10 to 40 µm. Monofilament fibres consist of a single continuous strand, whereas multifilament fibres are composed of several individual filaments combined together. Fibrillated fibres, although having comparable diameters to monofilament and multifilament types, are manufactured as thin films that are slit to allow expansion into an open, mesh-like network structure [18]. All fibre types can be cut to specific lengths, commonly between 3 and 20 mm. In recent years, alternative fibre materials such as polyvinyl alcohol, cellulose, nylon, and jute have also been explored; however, their performance in concrete applications has not yet been conclusively established.

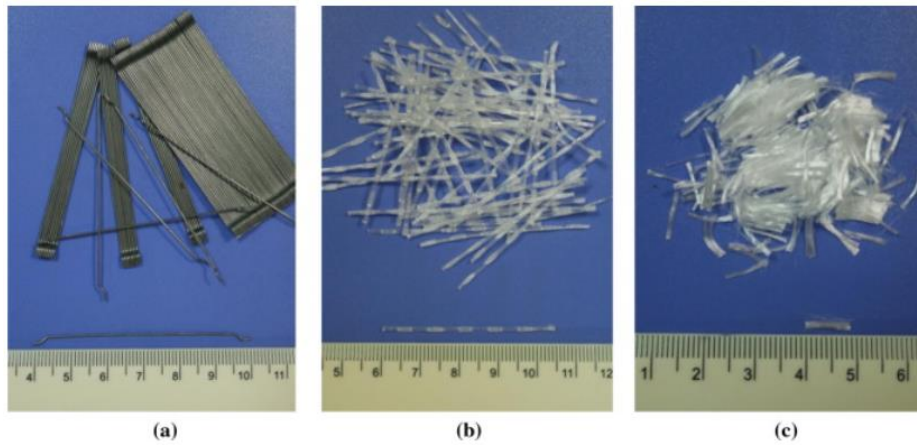


Figure 3-1[46]: Images of fibres (a) Steel fibre; (b) Macro PP fibre; (c) Micro PP fibre.

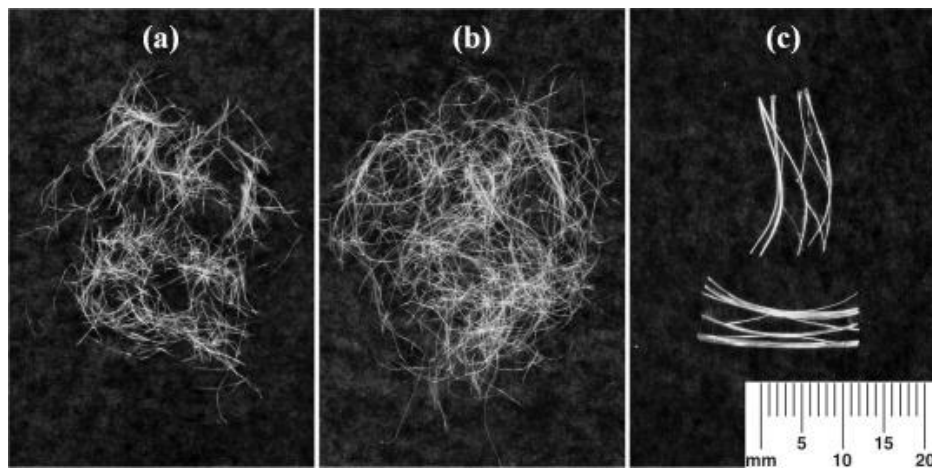


Figure 3-2 [18]: Photographs of (a) 6 mm monofilament ($32\ \mu\text{m}$ diameter), (b) 12 mm multifilament ($32\ \mu\text{m}$ diameter), and (c) 20 mm fibrillated ($37 \times 200\ \mu\text{m}^2$) PP fibres.

A total of 10 specimens were examined to assess their spalling behaviour. The experimental series included three steel fibre-reinforced concrete (FRC) specimens, three steel FRC specimens modified with polypropylene (PP) fibres, and four ordinary reinforced concrete specimens (ARM), three of which were uncoated while one was covered with a protective fire-resistive coating.

3.2 SPECIMEN DIMENSIONS

All specimens are prismatic blocks with nominal dimensions of 48 cm × 48 cm × 30 cm, as illustrated in Figure 3-3. Lifting anchors were embedded in the upper portion of the blocks to facilitate handling. The geometry allowed for exposure of one primary face during the fire test.

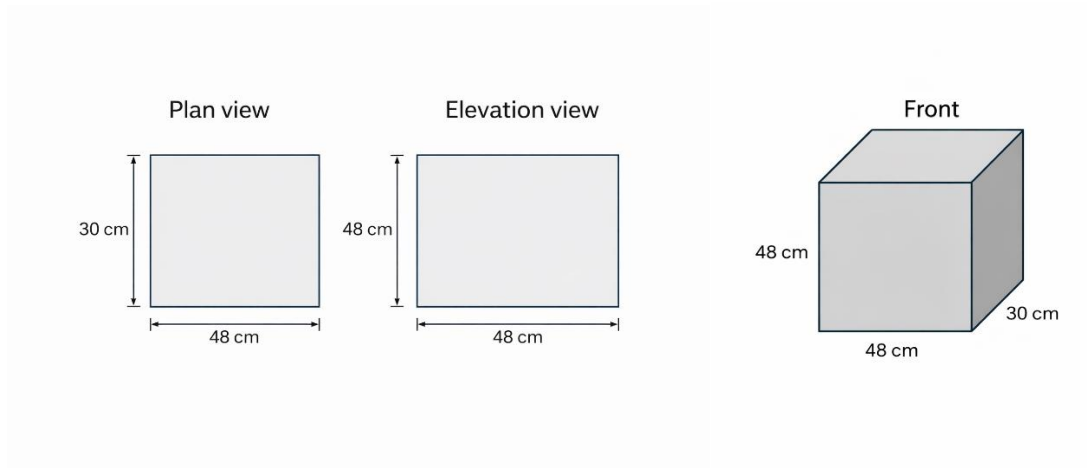


Figure 3-3: Specimen dimensions.

Moreover, the concrete block (480 × 480 × 300 mm) under investigation was drilled on the rear face with three holes to allow the installation of three thermocouples, in order to monitor the temperature development at different depths within the block. The first thermocouple was positioned at 25 cm from the rear face (i.e., 5 cm from the exposed surface), the second at 20 cm (10 cm from the exposed surface), and the third at 15 cm (15 cm from the exposed surface).

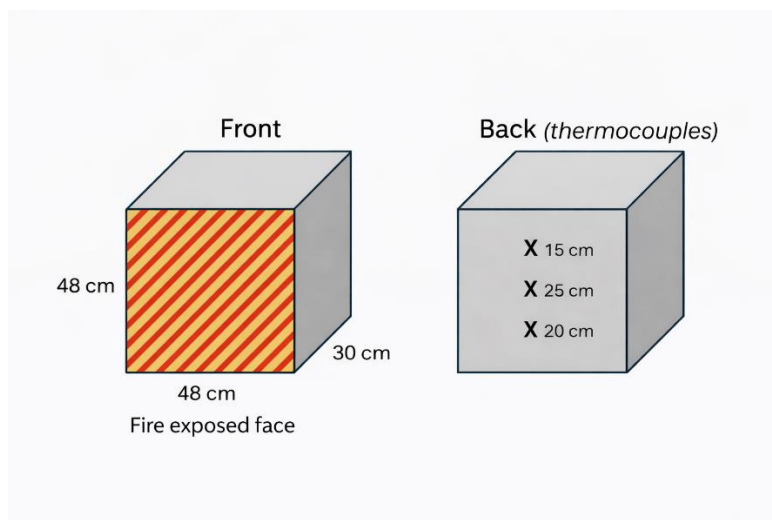


Figure 3-4: Fire exposed area and placement of thermocouples.

3.3 FIRE TEST

The fire exposure test analysed in this study was conducted externally at the laboratories of *J.F. Amonn S.r.l. (Ponte nelle Alpi, Italy)*. The present work is based on the official laboratory reports that describe fire resistance tests on concrete blocks conducted from 25th of May to 29th September of 2025. Concrete specimens were cured at least 90 days before each fire test was performed.

The specimens were subjected to fire exposure following the ISO 834 standard fire curve. The furnace used was equipped with a single methane burner positioned frontally to the exposed surface and regulated to follow the ISO 834 temperature–time relationship. The block was inserted into the furnace opening (14.5 cm depth), insulated at the edges with mineral fibre, and mechanically fixed using ratchet straps to ensure stability during testing.



Figure 3-5: Furnace equipped with a single burner (J.F. Amonn s.r.l.).



Figure 3-6: Specimen set-up in the furnace.

The test duration was 120 minutes, after which the specimen was removed and evaluated in terms of thermal transmission and spalling behaviour. Temperature evolution was monitored throughout the test via the embedded thermocouples and furnace measurements and subsequently, time-temperature curves of the furnace and thermocouples were developed.

This externally conducted fire resistance test forms the experimental basis for the subsequent analysis presented in this thesis.

The furnace temperature was continuously monitored and compared with the theoretical ISO 834 curve and the prescribed tolerance limits, which could be seen in Figure 3-7.

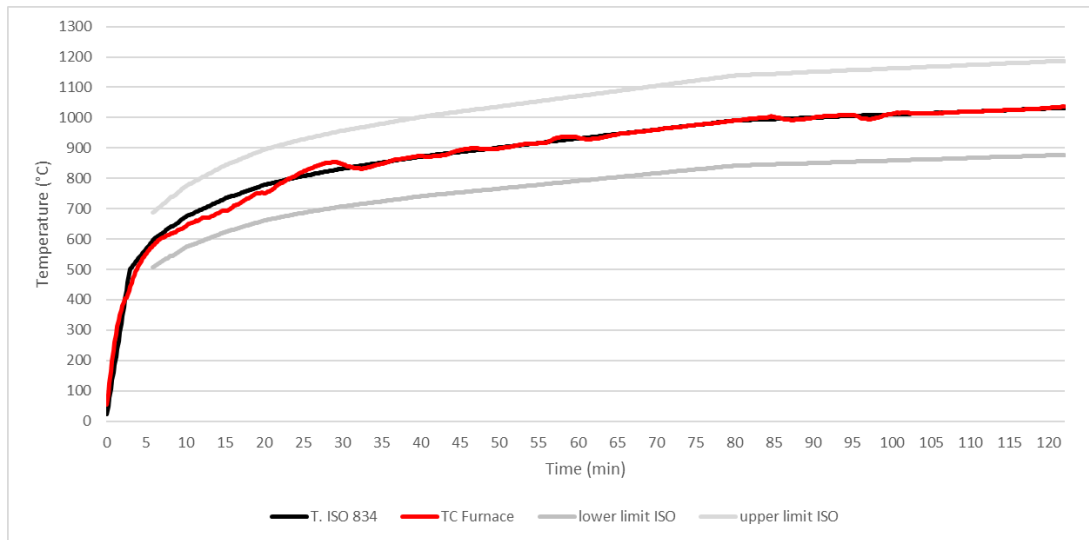


Figure 3-7: Furnace temperature.

In general, the furnace temperature followed the ISO 834 curve satisfactorily throughout the duration of the tests. Minor deviations were observed in some cases; however, the temperature remained within or close to the admissible ISO tolerance band. A temporary deviation was observed in test ARM 4, where a short reduction in furnace temperature occurred during the mid-stage of the test, followed by recovery.

Therefore, the boundary thermal conditions can be considered consistent and comparable across the test series.

3.4 POST-FIRE ASSESSMENT

3.4.1 3D scanning for geometrical data collection

After completion of the fire exposure tests, the damaged specimens were subjected to a geometric assessment in order to quantify the extent of material loss and determine the minimum remaining thickness.

Scanning Procedure

The specimens were digitized using a Revopoint MetroX 3D scanner based on blue laser line technology. According to manufacturer specifications, the scanner provides a single-frame accuracy of up to ± 0.02 mm, allowing high-resolution geometrical assessment of surface damage.

Considering scanner accuracy and alignment procedures, the overall geometrical uncertainty is estimated to be within ± 0.1 – 0.3 mm. Given that the measured spalling depths are in the order of several millimetres, the influence of instrumental uncertainty on the results is considered negligible.

The set-up is illustrated below.

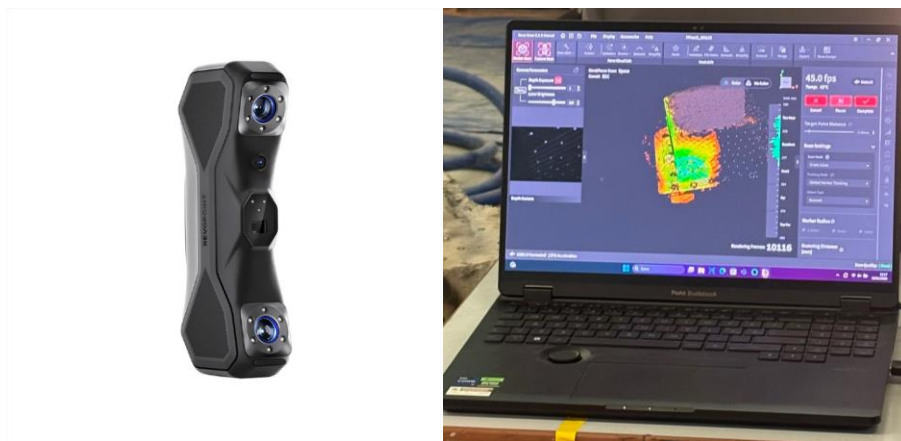


Figure 3-8: Revopoint MetroX 3D scanning system set-up.

Prior to scanning, adhesive markers were distributed across the specimen surfaces. These markers were used to facilitate automatic alignment and improve registration accuracy between multiple scans. Due to the highly irregular geometry of the fire-exposed surface, several scans were acquired from different orientations to ensure complete surface coverage.



Figure 3-9: Example of marked specimen ready for scanning.

The final output of the scanning process consisted of a dense point cloud representing the external surface of the fire-damaged block.

Due to the irregular geometry of the fire-exposed surface, multiple scans were acquired from different orientations to ensure complete coverage of the specimen. The presence of reference markers allowed accurate registration of the individual scans into a unified coordinate system.

After acquisition, the scans were used to obtain a dense point cloud and mesh representing the external geometry of the specimen.

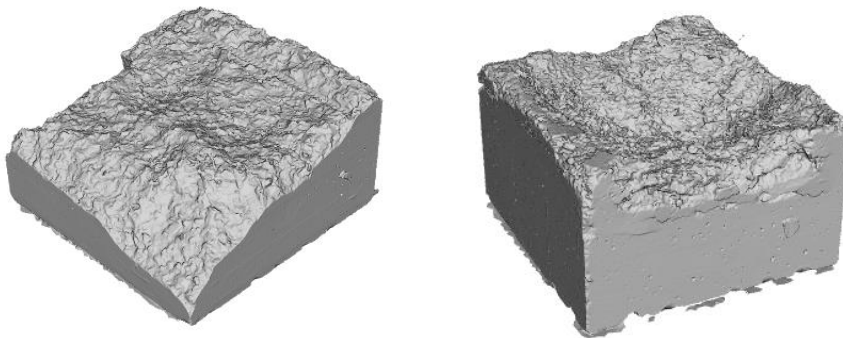


Figure 3-10: Examples of obtained mesh through 3D scanning.

Data Processing

The resulting point clouds were imported into *CloudCompare* for further processing and analysis. For each scanned specimen, the workflow consisted of:

1. Noise filtering and removal of isolated outlier points;
2. Segmentation of relevant surfaces (fire exposed face);
3. Alignment of the model within a consistent global coordinate system;
4. Calculation of cloud-to-cloud distance (max/mean/min values).

The rear surface was assumed to remain geometrically stable during fire exposure and was therefore used as the baseline for thickness calculations. The rear and exposed surfaces were manually segmented from the full point cloud.

The remaining thickness after spalling was determined using a cloud-to-cloud (C2C) distance computation in CloudCompare.

For each point belonging to the exposed surface, the nearest neighbour orthogonal distance to the rear surface point cloud was calculated, generating a scalar field representing the spatial distribution of residual thickness.

The minimum value of this scalar field was used as an indicator of minimum remaining thickness. Then, maximum spalling depth was calculated by the difference of initial thickness and minimum remaining thickness values.

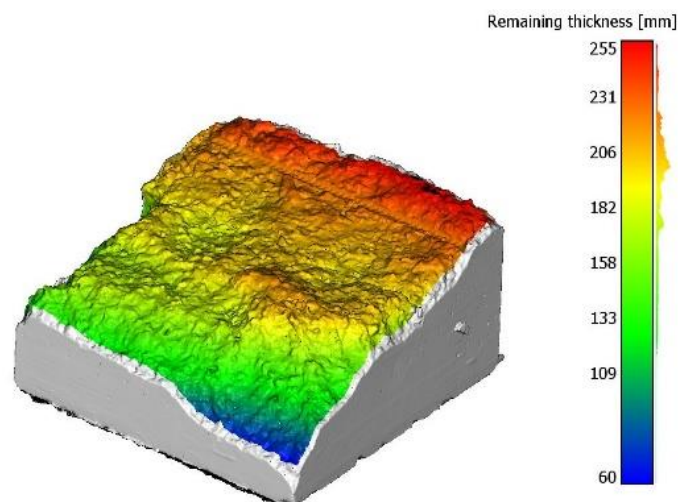


Figure 3-11: Example of developed thickness map.

3.4.2 Compressive tests

Spalling significantly deteriorates mechanical properties of RC, therefore, residual compressive strength of specimens was measured in the lab.

Core extractions

After completion of the fire exposure tests, cylindrical core samples were extracted from the concrete specimens in order to evaluate the residual mechanical properties of the material.

Following each extraction, two core specimens were prepared and cleaned to remove loose debris. One core nearest to fire exposed surface, and other furthest, later denoted as 1F (close from the exposed surface), and 2 (further). This was done to see the damage gradient throughout the thickness of the specimen. The dimensions of each core were measured, including diameter and height, in order to determine the exact geometry required for the compressive strength calculations. The extracted cores had a height-to-diameter ratio close to unity ($H/D \approx 1$), which is typical for core testing. Since all specimens exhibited similar geometrical proportions, the influence of specimen geometry on the measured compressive strength is considered negligible. The end surfaces of the cores were prepared to ensure proper contact with the testing machine platens. Fig.3-12 and 3-13 illustrates the core extraction set-up.



Figure 3-12: Core extraction.



Figure 3-13: Extracted cores.

Compressive tests on extracted cylinders

The prepared core cylinders were then subjected to axial compressive testing using a hydraulic compression testing machine. The load was applied continuously and monotonically until failure.



Figure 3-14: Compressive test set-up.

Since the height of the extracted cores were too small to measure strain, only compressive strength was evaluated for the damaged specimens. However, separate cylinders were prepared from the same mix that were not exposed to fire, to compare with those that were subjected to heating. Based on the obtained data, several parameters were determined, including the residual compressive strength, strain at peak stress, and the stress–strain relationship. These results also enabled estimation of the Young’s modulus, which characterizes the stiffness of the fire-exposed concrete.



Figure 3-15: Specimen after failure under compressive load.

The results of these tests provide important information about the degradation of mechanical properties after exposure to elevated temperatures.

4 RESULTS AND ANALYSIS

4.1 TEMPERATURE DEVELOPMENT

Internal temperatures were recorded using thermocouples positioned at three depths measured from the rear face of the specimen:

- 25 cm from the rear face (corresponding to 5 cm from the exposed surface),
- 20 cm from the rear face (10 cm from the exposed surface),
- 15 cm from the rear face (15 cm from the exposed surface).

As expected, the thermocouple located closest to the exposed surface (5 cm depth) exhibited the earliest and most significant temperature increase in all specimens. The deeper thermocouples showed delayed and attenuated thermal responses, confirming progressive heat penetration through the concrete thickness.

Notable differences were observed among the specimen groups (ARM, FRC, and PP), particularly in the rate of temperature increase and the maximum temperatures reached at each depth.

The differences in heat penetration at 5 cm, 10 cm, 10 cm depth from the exposed face of the specimens are illustrated by the time-to-temperature values reported in Tables 4-1,2,3.

Table 4-1: Time-to-temperature milestones for all specimens at 5 cm depth from the exposed face, showing the time required to reach 100 °C, 250 °C and 500 °C during fire exposure (NR = temperature not reached during the test).

Group	Specimen №	t100 (min)	t250 (min)	t500 (min)	Peak Temperature (°C)
ARM	1	24	27	31	1137
ARM	2	25	28	32	1146
ARM	3	66	97	NR	356
ARM + M-II	4	72	79	95	703
FRC	1	25	28	30	1012
FRC	2	24	33	83	796
FRC	3	22	25	27	1033
PP	1	38	61	NR	548
PP	2	28	32	47	585
PP	3	23	25	27	562

Table 4-2: Time-to-temperature milestones for all specimens at 10 cm depth from the exposed face, showing the time required to reach 100 °C, 250 °C and 500 °C during fire exposure (NR = temperature not reached during the test; NM=not measured).

Group	Specimen №	t100 (min)	t250 (min)	t500 (min)
ARM	1	98	NR	NR
ARM	2	102	NR	NR
ARM	3	NR	NR	NR
ARM+ M-II	4	89	NR	NR
FRC	1	NM	NM	NM
FRC	2	51	108	NR
FRC	3	40	97	NR
PP	1	66	NR	NR
PP	2	86	NR	NR
PP	3	81	NR	NR

Table 4-3: Time-to-temperature milestones for all specimens at 10 cm depth from the exposed face, showing the time required to reach 100 °C, 250 °C and 500 °C during fire exposure (NR = temperature not reached during the test; NM=not measured).

Group	Specimen №	t100 (min)	t250 (min)	t500 (min)
ARM	1	NR	NR	NR
ARM	2	89	NR	NR
ARM	3	NR	NR	NR
ARM+ M-II	4	NR	NR	NR
FRC	1	NM	NM	NM
FRC	2	114	NR	NR
FRC	3	87	NR	NR
PP	1	NR	NR	NR
PP	2	NR	NR	NR
PP	3	NR	NR	NR

4.1.1 Ordinary Reinforced Concrete Specimens

In general, ordinary reinforced concrete specimens exhibited the fastest temperature increase at 5 cm depth and reached the highest peak temperature among the three. Thermocouples at 5 cm depth from the exposed face of ARM specimens measured 200 °C in 25 minutes, when intense vaporization happens within concrete. They were exceeding 600 °C in around 40 minutes, when intense crumbling of specimens was observed. On average, specimens reached more than 1000 °C near the exposed surface by the end of the test.

However, it is worth to note that the third specimen made up only from ordinary concrete showcased relatively low temperature development: reaching only up to maximum of 400 °C within 5 cm depth from exposed surface by the end of the fire exposure. This further is confirmed by the relatively low spalling depth and overall less damage compared to other specimens from the same mix. Therefore, it is important to consider the group average and take into account variability while comparing different mixtures.

The specimen coated with the protective layer (ARM4) showed a significant delay in temperature development (reaching 100°C only at 70 min) and lower peak temperature than the uncoated ARM specimens, reaching approximately 700°C at 5 cm depth. This suggests that the protective coating delayed heat penetration and limited the severity of thermal damage. Coated reinforced concrete specimen is measured to be among the most thermally resistant configurations at the 5 cm depth.

4.1.2 Fibre Reinforced Concrete Specimens

Steel Fiber Reinforced Concrete specimens showed a more gradual temperature rise, however, not significant difference compared to ordinary reinforced concrete.

Polypropylene fibres were observed to perform overall the best under fire exposure, as during the heating, PP modified specimens reached only up to 550°C at 5cm depth from exposed face, which is a significant difference compared to concrete without PP fibres.

The lower peak temperatures observed in PP-modified specimens may be attributed to the melting of polypropylene fibres, which increases permeability and facilitates vapor release. Additionally, reduced spalling in these specimens likely limited direct exposure of deeper layers to fire, resulting in lower recorded temperatures compared to ARM specimens.

At greater depths, the temperature increase was significantly delayed and attenuated compared to the measurements at 5 cm from the exposed face. At 10 cm depth, only a limited number of specimens reached 250°C and none reached 500°C, while at 15 cm depth the thermal response was further reduced, with only a few specimens exceeding 100°C during the test. Overall, these results indicate that heat penetration decreased significantly through the specimen thickness, and that the most severe thermal exposure remained concentrated in the near-surface zone.

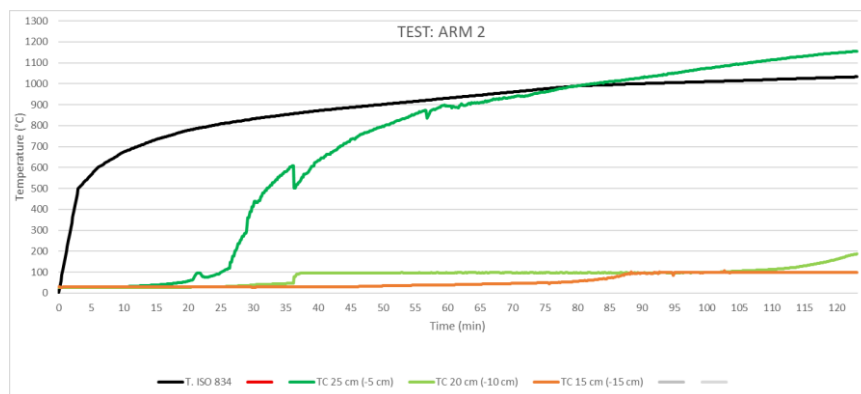


Figure 4-1: Time-Temperature curve representative of behaviour of ordinary reinforced concrete (ARM).

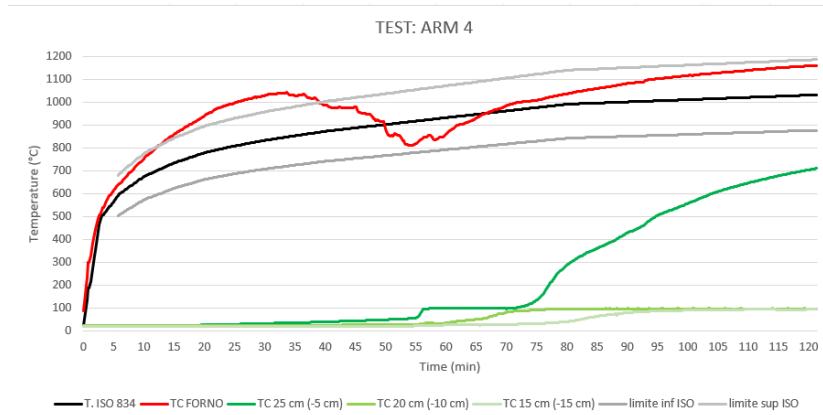


Figure 4-2: Time-Temperature curve of the specimen coated with fire protective layer (ARM4).

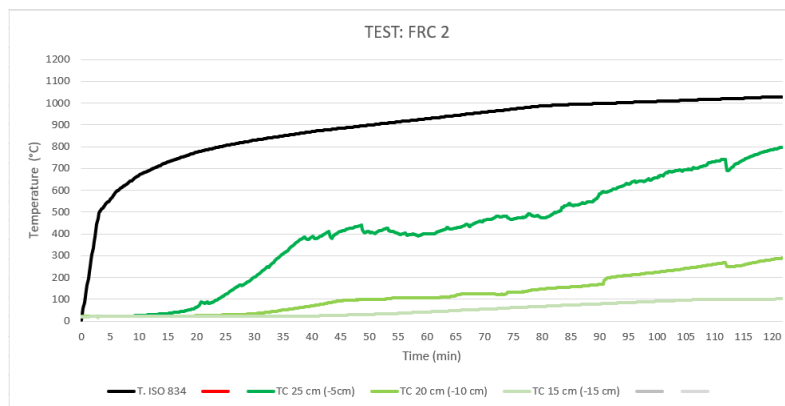


Figure 4-3: Time-Temperature curve representative of behaviour of Steel Fibre Reinforced Concrete (FRC).

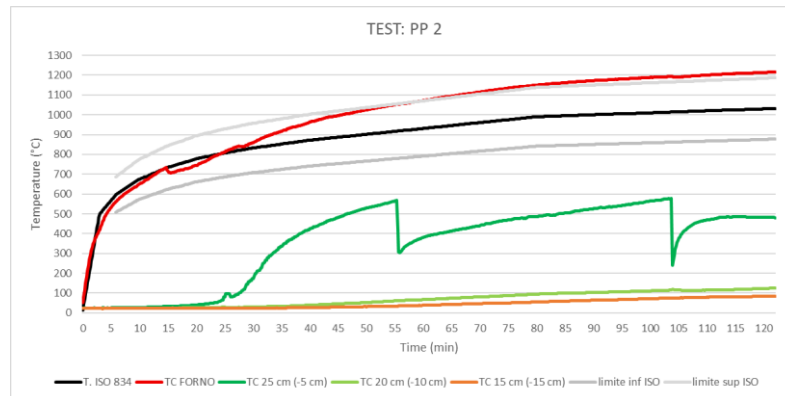


Figure 4-4: Time-Temperature curve representative of behaviour Polypropylene Reinforced Concrete (PP).

In several specimens, localized deviations from the general temperature trend were observed, primarily at the thermocouple positioned 5 cm from the exposed surface. These deviations appeared as abrupt drops or step-like variations in the recorded temperature curves. Since the specimens were subjected to continuous ISO fire exposure, such temperature reductions cannot represent actual cooling of the material. They are therefore attributed to local phenomena occurring during spalling events, such as partial loss of thermocouple contact, cracking around the sensor, or minor displacement of the measuring junction. These effects were observed across ARM, FRC, and PP specimens, although they were more pronounced in specimens exhibiting greater surface damage.

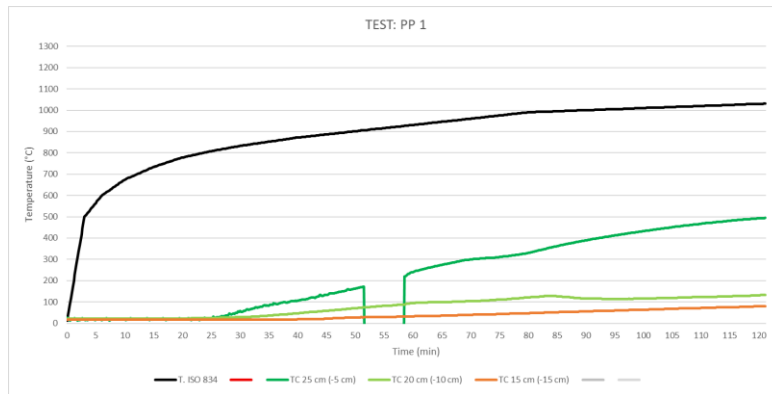


Figure 4-5: Example of temperature curve deviation caused by thermocouple disturbance during spalling

The complete set of temperature curves for all specimens is provided in Appendix A.

4.2 ASSESSMENT OF FIRE-INDUCED DAMAGE

4.2.1 Visual observation of fire-induced damage

The fire exposure resulted in extensive surface deterioration, particularly in the central region of the specimens directly exposed to thermal loading. Explosive spalling was observed within the first minutes of heating, coinciding with furnace temperatures exceeding 400–500°C.

In ARM specimens, severe material detachment occurred, leading to the exposure of reinforcement bars. In some cases, the reinforcement mesh partially detached from the concrete matrix. In the worst observed case (ARM 1), the central thermocouple positioned at 5 cm from the exposed face became fully visible after approximately 35–40 minutes of fire exposure, indicating substantial local thickness loss. The exposed face was completely detached, even revealing detached reinforcement bars.

Despite being exposed to identical fire conditions, the ARM specimens varied in the intensity of spalling damage, which is later confirmed by quantities results. This highlights the pronounced specimen-to-specimen variability of fire-induced spalling.



Figure 4-6: ARM specimen after fire exposure.

Steel Fiber reinforced concrete (FRC) specimens exhibited reduced fragmentation, and more crater- like damage. Although surface cracking and partial detachment were observed, reinforcement exposure was less extensive. Specimens showed more uniform results across the tests compared to ordinary reinforced concrete specimens.



Figure 4-7: FRC specimen after fire exposure.

PP-modified specimens showed predominantly progressive surface degradation rather than sudden explosive failure. After melting, the polypropylene fibres contributed to the formation of compacted concrete fragments, as the remaining material cooled and bonded into dense residual blocks. No complete reinforcement detachment was observed, and the residual block maintained greater structural integrity.



Figure 4-8: PP specimen after fire exposure.

All sets of photos of visual damage are provided in Appendix A.

A more detailed and quantitative assessment of the damage, based on 3D geometrical analysis, is presented in the following section.

4.2.2 Maximum spalling depth

The geometrical assessment of the fire-exposed specimens revealed significant differences in the residual thickness distribution and spalling severity among the investigated concrete types. The analysis was conducted considering the nominal initial thickness of 300 mm as reference.

The results obtained for each specimen are summarized in Table 4.4. The minimum remaining thickness, denoted in the table as d_0 , was identified as the smallest measured distance between the exposed surface and the reference rear plane. The mean spalling depth, $d_{\text{meanspalling}}$, throughout specimens were calculated and reported. The maximum spalling depth, $d_{\text{maxspalling}}$, was calculated as the difference between the initial specimen thickness and the minimum remaining thickness after fire exposure.

Table 4-4: Mean and maximum values of thickness induced by fire.

Test №	d_0 [mm]	d_{min} [mm]	$d_{\text{meanspalling}}$ [mm]	std.dev [mm]	$d_{\text{maxspalling}}$ [mm]
ARM (ordinary reinforced concrete)					
1	300	59	113	37	241
2	300	155	47	18	145
3	300	234	20	9	67
ARM+ M-II					
4	300	148	45	17	152
FRC (Steel Fibre reinforced concrete)					
1	300	165	44	28	135
2	300	155	47	25	145
3	300	160	53	31	140
PP (Polypropylene-fibre modified concrete)					
1	300	213	39	17	87
2	300	231	21	15	69
3	300	209	23	18	91

The maximum spalling depth represents the most severe localized material loss occurring within the fire-exposed surface. It reflects the worst-case damage scenario and is particularly relevant from a structural safety perspective, as localized deep spalling may significantly reduce the effective cross-section and expose reinforcement to elevated temperatures.

However, maximum spalling depth should be interpreted with caution, as it may be influenced by isolated extreme events. Therefore, it is most meaningful when evaluated in conjunction with global indicators such as mean spalling depth and standard deviation, allowing for a balanced assessment of both severity and distribution of fire-induced damage.

In general, the ordinary reinforced concrete specimens (ARM) exhibited the lowest minimum remaining thickness values, indicating more severe material loss due to fire-induced spalling.

For the coated specimen ARM4, the maximum spalling depth was 152 mm, which is close to ARM2 (145 mm) and considerably lower than the extreme damage observed in ARM1 (241 mm). This indicates that, although severe localized spalling still occurred, the protective layer appears to have reduced the severity of the worst-case damage compared to the most

vulnerable ordinary ARM specimen. Because only one coated specimen was tested, ARM4 is discussed separately rather than included in the ARM group average.

Figure 4-9 visualizes the comparative maximum spalling depth values of different specimen series.

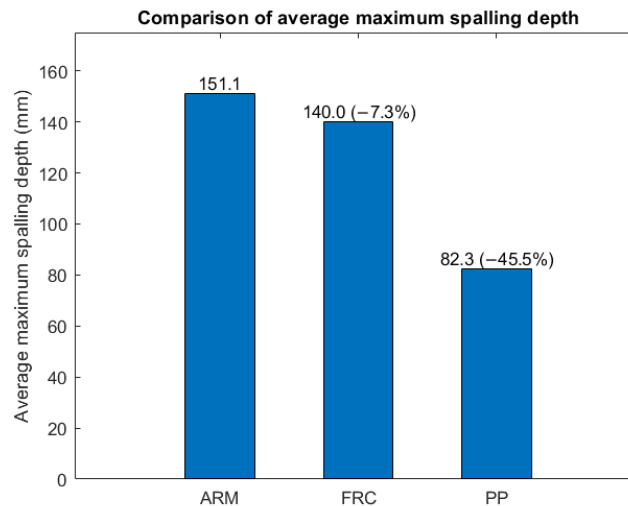


Figure 4-9: Average values of maximum spalling depth measured for specimens.

It was observed that Steel Fiber Reinforced concrete has slightly less spalling damage in terms of spalling depth: around 7% compared to ordinary concrete. While specimens modified by polypropylene fibres reduced the maximum spalling depth for more than 45% compared to ordinary concrete.

Although it is crucial to identify and assess the critical parameter such as maximum spalling depth, as it is the worst-case scenario, it is also interesting to understand the thickness distribution along the fire exposed surface of the specimen.

4.2.3 Mean spalling depth and deviations

Mean spalling depth represents the average material loss across the entire fire-exposed surface and therefore provides a global indicator of degradation severity. Unlike the maximum spalling depth, which reflects a localized extreme condition, the mean value characterizes the overall performance of the specimen under fire exposure. For comparative purposes between different concrete mixtures, the mean spalling depth offers a more representative and stable parameter, as it accounts for the entire damaged surface rather than isolated critical points.

In addition to the mean value, the standard deviation of spalling depth is essential for assessing the uniformity of damage distribution. A high standard deviation indicates significant spatial variability, suggesting localized explosive spalling or crater formation. Conversely, a low standard deviation reflects a more homogeneous and progressive degradation pattern. Therefore, while the mean spalling depth quantifies the extent of material loss, the standard deviation provides insight into the stability and consistency of the damage mechanism.

Together, these two parameters allow for a comprehensive evaluation of fire-induced spalling, capturing both the magnitude of degradation and the spatial distribution of damage across the specimen surface.

Damage patterns: Thickness maps

Ordinary concrete thickness maps demonstrated pronounced localized depressions in the central fire-exposed region and in some cases, detachment in the edges, suggesting concentrated damage zones. The variability of thickness, reflected by the standard deviation values, was also higher in ARM specimens, indicating non-uniform degradation across the exposed surface (see Fig.4-10).

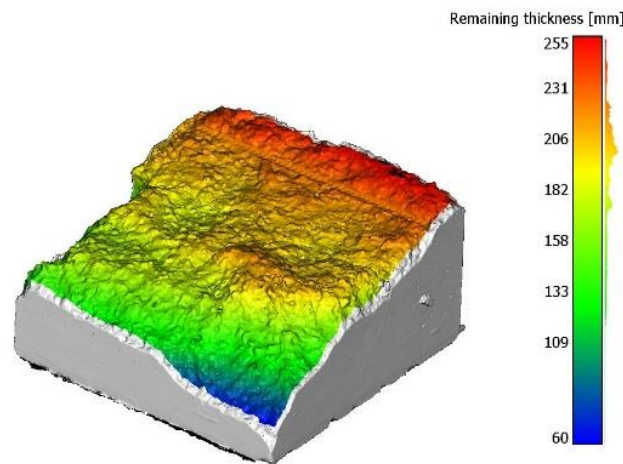


Figure 4-10: Example of thickness distribution of ARM specimens (ARM1).

Fiber-reinforced concrete specimens (FRC) showed a more moderate reduction in thickness. Although local spalling was still observed, the affected areas were generally smaller and less severe compared to ARM specimens. The damage observed among the specimens is more uniform and less varied compared to the ones of ARM. However, deviation numbers and visual inspection suggests that FRC specimens experienced intense localized central crater-like damage compared to some ARM specimens (see Fig.4-11).

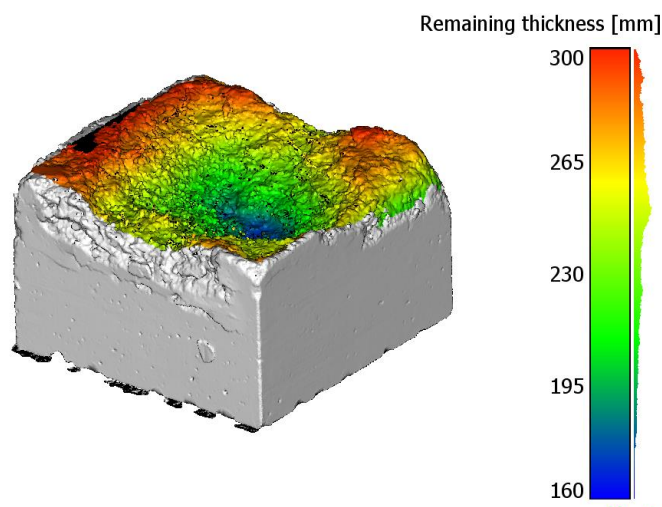


Figure 4-11: Example of thickness distribution of FRC specimens (FRC3).

The PP-modified fibre-reinforced concrete specimens demonstrated the highest minimum remaining thickness values and the lowest maximum spalling depths among the three groups. The surface profiles indicated more progressive and shallow material loss rather than abrupt detachment. The reduced variability suggests a more uniform response to thermal exposure (see Fig.4-12).

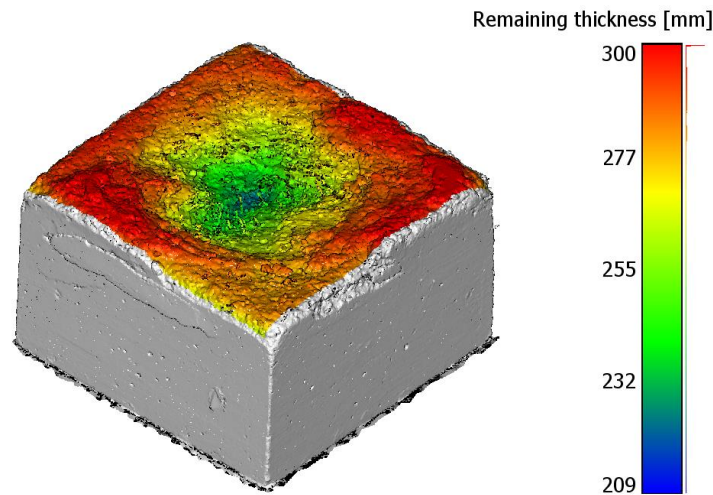


Figure 4-12: Example of thickness distribution of PP specimens (PP3).

All thickness maps are provided in Appendix A.

The percentage distribution of material loss classes reveals significant differences in spalling behaviour among the investigated specimen groups(Fig.4-5).

Table 4-5: Percentage distribution of spalling depth loss across the exposed surface for ARM, FRC and PP specimens.

No	% ≤ 25 mm loss	% 25-50 mm loss	% > 50 mm loss
ARM			
1	0	1	99
2	13	42	45
3	71	29	0
ARM+ M-II			
4	8	61	31
FRC			
1	31	31	38
2	22	35	43
3	21	31	48
PP			
1	26	42	32
2	70	24	6
3	63	27	10

The ARM specimens exhibited the highest variability. While ARM1 showed an almost complete severe degradation, with approximately 98.5% of the surface experiencing material

loss greater than 5 cm, ARM3 retained the majority of its surface within the 0–25 mm loss range. This highlights the stochastic and highly localized nature of explosive spalling in conventional reinforced concrete. More than 5cm thickness loss signifies at least more than 10 % depth loss from the whole thickness, which can affect the structural integrity.

In contrast, the SFRC specimens demonstrated a more distributed damage pattern. Although a considerable portion of the surface (approximately 38–48%) experienced losses exceeding 5 cm, the degradation was less globally critical than in the most severely affected ARM specimen. The presence of fibres appears to contribute to a more gradual redistribution of cracking and damage propagation.

The PP-modified specimens generally exhibited the most controlled behaviour. In two out of three cases (PP2 and PP3), more than 60% of the surface experienced material loss below 2.5 cm, while the proportion of regions exceeding 5 cm loss remained limited. This behaviour supports the hypothesis that polypropylene fibres enhance permeability during heating, thereby reducing pore pressure build-up and mitigating severe explosive spalling.

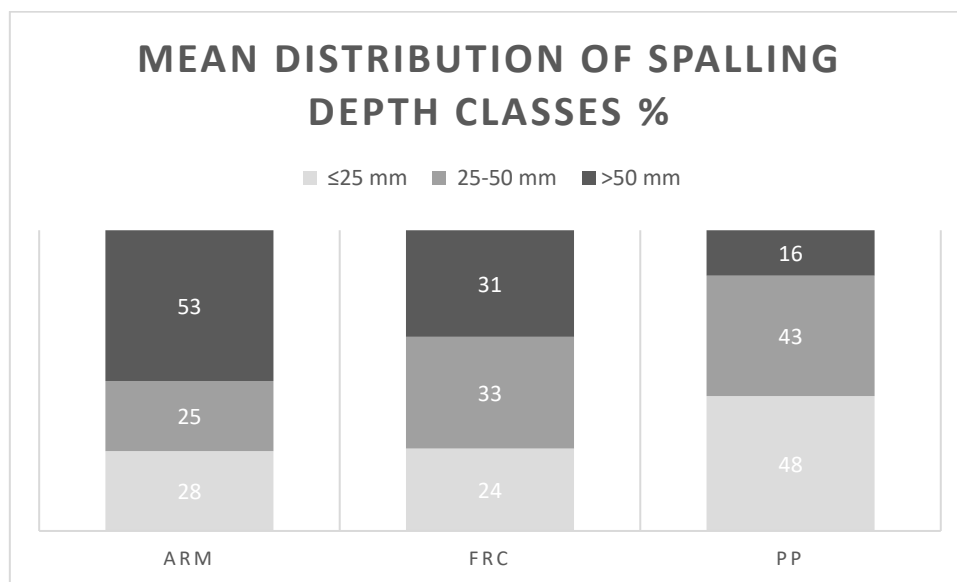


Figure 4-13: Mean distribution of spalling depth classes across the exposed surface for ARM, FRC and PP groups. Percentages are calculated based on the ratio of surface points within defined material loss intervals (initial thickness = 300 mm).

When comparing 3 different series of specimens, clear trend is observed:

ARM specimens experienced the greatest spalling severity, followed by FRC, while PP-modified specimens showed the best preservation of structural thickness. This hierarchy is consistent across minimum thickness, maximum depth, and volumetric loss indicators.

Furthermore, the spatial distribution of thickness reduction revealed that spalling was predominantly concentrated in the central region of fire exposure, where thermal gradients were most intense. Edge regions generally retained larger thickness values, indicating lower thermal and mechanical damage away from the directly exposed zone.

4.2.4 Volume loss

The volume loss caused by fire-induced spalling was quantified by comparing the original specimen volume with the remaining volume measured from the 3D scans after the fire test. The initial volume of the specimens (V_0) was calculated based on the nominal dimensions of the concrete blocks ($480 \times 480 \times 300$ mm), corresponding to $69,120 \text{ cm}^3$.

The final volume (V_{fin}) was obtained from the processed 3D meshes of the post-fire specimens. The percentage of volume loss was then calculated.

Table 4-6 summarizes the calculated values of the initial volume, remaining volume, and corresponding percentage of volume loss for each specimen.

Table 4-6: Volume loss of specimens after fire exposure.

Nº	$V_0 [\text{cm}^3]$	$V_{\text{fin}} [\text{cm}^3]$	$V_{\text{loss}} [\%]$
ARM			
1	69120	43247	37.4
2	69120	58330	15.6
3	69120	64700	6.4
ARM+ M-II			
4	69120	58634	15.2
FRC			
1	69120	59602	13.8
2	69120	59047	14.6
3	69120	57597	16.7
PP			
1	69120	60137	13.0
2	69120	65298	5.5
3	69120	64067	7.3

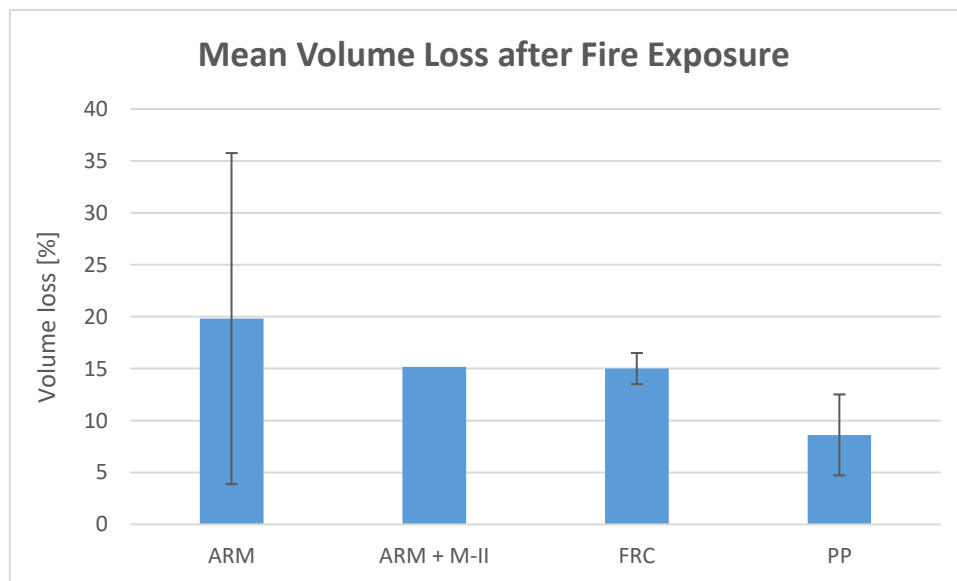


Figure 4-14: Mean volume loss of concrete specimens for the investigated mixtures (error bars represent standard deviation).

The results indicate significant differences between the investigated concrete mixtures.

The ordinary reinforced concrete specimens (ARM) exhibited the highest variability and the largest volume loss. In particular, Test 1 showed severe explosive spalling with a volume loss of 37.4%, while Test 3 exhibited considerably lower damage (6.4%). This variability suggests that spalling behaviour in conventional reinforced concrete can be highly unpredictable even within specimens of the same mixture.

Ordinary reinforced concrete with protective coating (ARM+ M-II) showed a volume loss of 15.2%, very close to ARM2 (15.6%) and within the range of the FRC specimens. This is much lower than the severe loss measured for ARM1 (37.4%), indicating that ARM4 did not undergo the same level of damage. However, its performance was still less favourable than that of the PP-modified specimens.

The steel fibre reinforced concrete (FRC) specimens demonstrated more consistent behaviour. The volume loss values ranged between 13.8% and 16.7%, indicating a more stable damage pattern compared to ARM specimens. The presence of fibres likely contributed to limiting crack propagation and restraining large spalling events.

The polypropylene fibre modified concrete (PP) specimens showed the lowest overall damage. Volume loss ranged from 5.5% to 13%, with an average significantly lower than the other specimen groups. This behaviour is consistent with the known mechanism of polypropylene fibres melting at elevated temperatures, which creates additional pore channels allowing vapor pressure to dissipate and thus reducing the likelihood of explosive spalling.

The results indicate that the ARM specimens exhibit the highest variability in volume loss, as reflected by the large standard deviation. In contrast, FRC specimens demonstrate more consistent behaviour, while PP-modified concrete shows the lowest mean volume loss, confirming the effectiveness of polypropylene fibres in mitigating explosive spalling.

Overall, the results confirm that polypropylene fibres significantly reduce the severity of fire-induced spalling, while conventional reinforced concrete specimens may exhibit highly localized and severe damage.

4.2.5 Residual Compressive Strength

The residual compressive strength of the concrete specimens was evaluated through compression tests performed on cylindrical cores extracted from different regions of the fire-exposed slabs. In particular, two cores were obtained from each specimen: one located near the fire-exposed surface (denoted as *1F*) and one from the bottom region (2), representing a less thermally affected zone.

The compressive strength values, expressed as the stress at failure, were correspond to the ratio between the maximum applied load and the cross-sectional area of the cores. The results are summarized in Tables 4-7, 4-8.

$$f_c = \frac{F}{A}$$

where:

- F = maximum load at failure
- A = cross-sectional area.

Table 4-7: Residual compressive strength of core specimens extracted near fire exposed face=.

Core №	Density (kg/m³)	f _c (MPa)
ARM		
ARM1z 1F	2285	24.3
ARM2z 1F	2236	16.8
ARM3z 1F	2301	41.9
ARM+ M-II		
ARM4z 1F	2274	26.3
FRC		
FRC1z 1F	2249	24.5
FRC2z 1F	2251	15.9
FRC3z 1F	2241	21.3
PP		
PP1z 1F	2238	31.8
PP2z 1F	2238	23.8
PP3z 1F	2245	19

Table 4-8: Residual compressive strength of core specimens extracted further from fire exposed face.

Core №	Density (kg/m ³)	fc (MPa)
ARM		
ARM1z 2	2365	75.6
ARM2z 2	2351	69.2
ARM3z 2	2345	65.1
ARM+ M-II		
ARM4z 2	2364	72.8
FRC		
FRC1z 2	2328	73.6
FRC2z 2	2351	80.3
FRC3z 2	2349	75.4
PP		
PP1z 2	2321	75.7
PP2z 2	2342	81.1
PP3z 2	2350	69.5

Tables 4-7 and 4-8 show a clear distinction in compressive strength between cores extracted near the fire-exposed surface (*1F*) and those taken from the inner region (*2*) across all mixes. The *1F* specimens exhibit significantly reduced strengths (approximately 16–42 MPa), while the *2* specimens retain much higher values (65–81 MPa), corresponding to an increase of about 2.5 to 3 times. When comparing the mixes, ARM shows the highest average strength in the exposed region (~27 MPa), followed by PP (~25 MPa), whereas FRC exhibits the lowest (~21 MPa), suggesting that polypropylene fibres may slightly mitigate damage due to increased permeability at high temperatures. In contrast, in the inner region, all mixes display similar strength levels (approximately 70–76 MPa), indicating that the influence of mix composition becomes negligible where thermal exposure is limited. Overall, the results confirm that thermal damage is highly localized and governs the residual mechanical performance of the concrete.

Table 4-9: Summary of residual compressive strength of core specimens grouped by mix type and extraction depth.

Mix Type	Position	Mean Strength (MPa)	Min (MPa)	Max (MPa)	Sd (MPa)
ARM	1F	27.7	16.8	41.9	12.7
ARM	2	70	65.1	75.6	5.3
ARM + M-II	1F	26.3			-
ARM + M-II	2	72.8			-
FRC	1F	20.6	15.9	24.5	4.4
FRC	2	76.4	73.6	80.3	3.4
PP	1F	24.9	19	31.8	6.5
PP	2	75.4	69.5	81.1	5.8

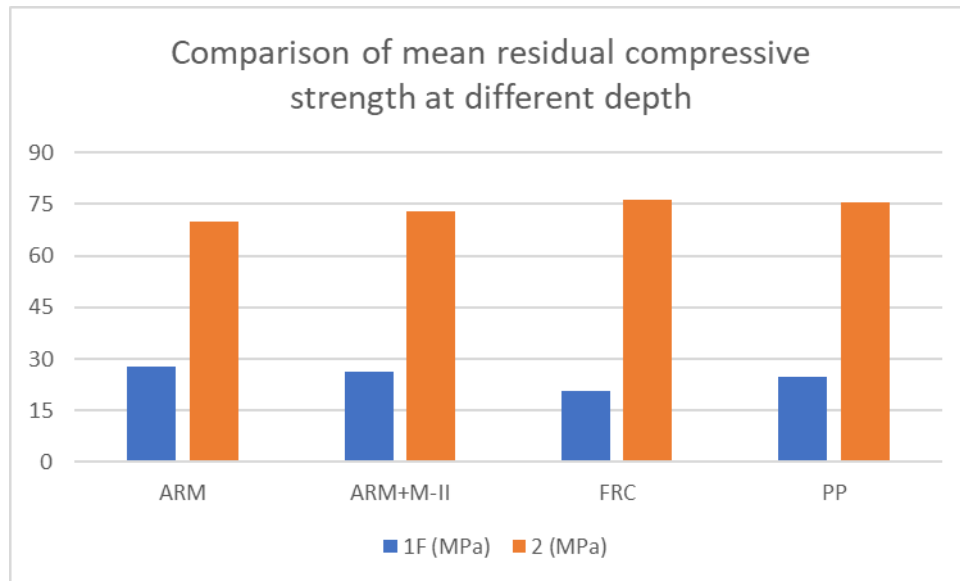


Figure 4-15: Comparison of residual compressive strength of core specimens for different concrete mixes at varying depths (1F and 2).

Figure 4-15 illustrates the residual compressive strength of core specimens for different concrete mixes, comparing values obtained near the fire-exposed surface (1F) and from the inner region (2). A significant reduction in strength is observed in the 1F cores across all mixes, with values ranging approximately between 20 MPa and 30 MPa, while the inner cores consistently exhibit much higher strengths between 70 MPa and 80 MPa. This highlights the strong influence of thermal exposure and confirms that damage is primarily concentrated near the exposed surface. Differences between mixes are more noticeable in the fire-exposed region, where PP specimens show slightly higher residual strength, whereas in the inner region the values are relatively similar for all mixes, indicating limited influence of material composition under lower thermal exposure.

A higher standard deviation is observed in the fire-exposed region (1F), particularly for ARM specimens, indicating a greater variability in damage due to the heterogeneous nature of fire-induced degradation. Moreover, on average, cores extracted from exposed surface of specimens without fibres exhibited highest compressive strength, ARM 3 being the best performing among the mixes with around 42 Mpa. When excluding the highest value observed in the ARM group, the average compressive strength of the near-surface cores decreases to approximately 20.6 MPa. Under this condition, the PP specimens exhibit the highest residual strength, followed by ARM and FRC.

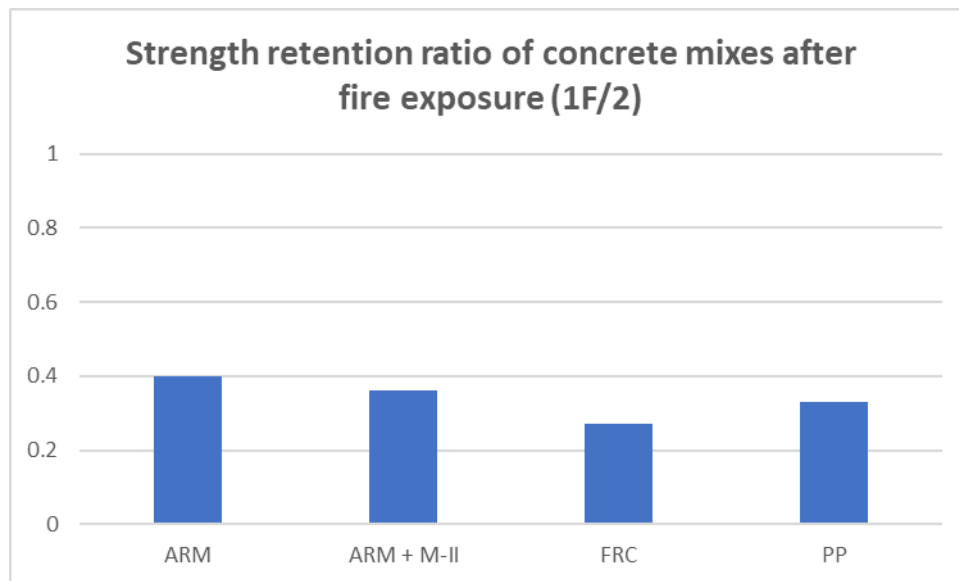


Figure 4-16: Ratio of residual compressive strength between fire-exposed (1F) and inner (2) cores for different concrete mixes.

Figure 4-16 presents the strength retention ratio, defined as the ratio between compressive strength in the fire-exposed region (1F) and the inner region (2). The results indicate that all concrete mixes retain only 27% to 40% of their original strength near the exposed surface, confirming the severe impact of fire exposure. Among the tested mixes, ARM shows the highest retention, followed by ARM + M-II and PP, while FRC exhibits the lowest value. However, the relatively higher retention observed for ARM is influenced by variability in the results and should be interpreted with caution. Overall, the diagram highlights that, regardless of mix composition, a significant loss of mechanical capacity occurs in the fire-exposed region.

4.3 DISCUSSION AND INTERPRETATION OF RESULTS

The results presented in the previous sections showed that the tested specimens did not respond uniformly to fire exposure, either in terms of temperature development or in the extent and form of the resulting damage. Such differences should not be interpreted only as isolated experimental outcomes, but rather in relation to the physical mechanisms governing fire-induced spalling in concrete. Indeed, spalling is widely recognised as a complex phenomenon resulting from the interaction of several coupled processes, including moisture evaporation, vapour migration, pore pressure build-up, restrained thermal dilation, and progressive internal cracking [6]. The relative importance of these mechanisms depends on a number of factors, such as concrete composition, permeability, moisture content, heating rate, and boundary conditions. Consequently, the behaviour observed in the present experimental campaign is discussed not as the consequence of a single governing cause, but as the outcome of a combined thermo-hydro-mechanical response of the material under severe thermal loading.

4.3.1 Analysis of spalling behaviour of ordinary concrete specimens

In the case of ordinary reinforced concrete specimens without fibres, the observed behaviour may be interpreted in light of the pore-pressure-based explanation of spalling commonly reported in the literature. Several studies have reported that [47], in concrete sections exposed to fire without fibre modification, the intersection between the increasing pore pressure and the decreasing tensile resistance of concrete often occurs within a temperature range of approximately 200 to 300°C, which is considered a critical interval for the occurrence of spalling. Concrete subjected to one-sided fire exposure, moisture migration from the heated surface toward the colder inner core may lead to the formation of a saturated zone beneath the exposed face, commonly referred to as a moisture clog[47]. This slows down vapor transport and promotes a temporary build-up of pore pressure. At the same time, the tensile strength of concrete decreases with increasing temperature. Spalling may therefore occur when the developing internal pressure coincides with a significant thermal weakening of the near-surface concrete. As heating progresses further, drying, microcracking, and permeability increase may facilitate vapor escape, resulting in a reduction of pore pressure[48].

This suggests that, in the absence of fibres, the reduction in tensile strength combined with limited permeability may lead to earlier mechanical instability, both in terms of temperature and exposure time. The severe damage observed in the ARM specimens (volume loss up to 35%) confirms the lack of an internal pressure-relief mechanism.

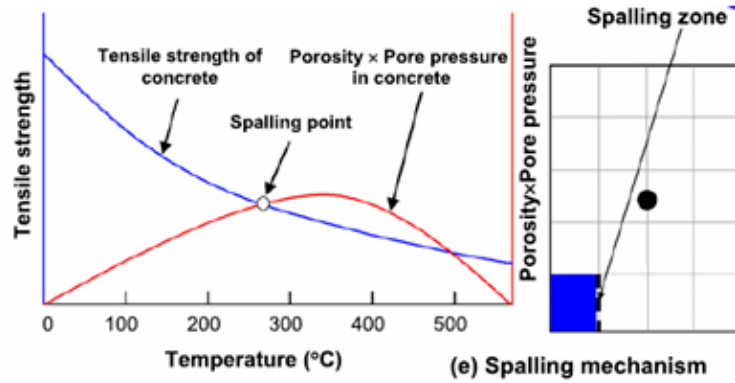


Figure 4-17[47]:Spalling mechanism in a concrete section.

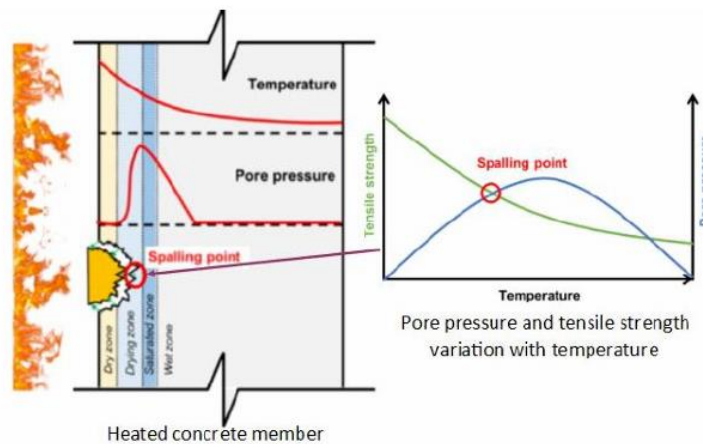


Figure 4-18[48]:Evolution of pore pressure and temperature within the concrete element.

As discussed in Section 4.1, the thermocouple measurements at different depths showed that, under one-sided fire exposure, the ARM specimens developed steep thermal gradients between the exposed face and the colder inner core. This could have led restrained thermal dilation to create additional internal stresses within the specimen cross section. The combined action of pore pressure build-up and thermal gradient mechanisms provides a plausible explanation for the severe spalling, reinforcement exposure, and local loss of section observed in this group. Fig.4-18 illustrates the combined mechanisms acting on a heated concrete member exposed to fire on one side[48].

A notable feature of the ARM series was the pronounced variability in spalling severity among specimens of the same group (Fig.4-19). Although these specimens had the same nominal concrete composition and were subjected to the same general fire scenario, their damage levels differed. This scatter highlights the inherently unstable nature of fire-induced spalling in ordinary reinforced concrete. The phenomenon is highly sensitive to local factors such as moisture distribution, pore connectivity, permeability, pre-existing microcracking, and the development of vapor escape paths during heating. As a result, small internal differences between nominally identical specimens may lead to different spalling outcomes.

Moreover, observed maximum spalling depth of specimens and standard deviation values point that the fire exposed surface of the specimens experienced irregular and localised damage along the surface.

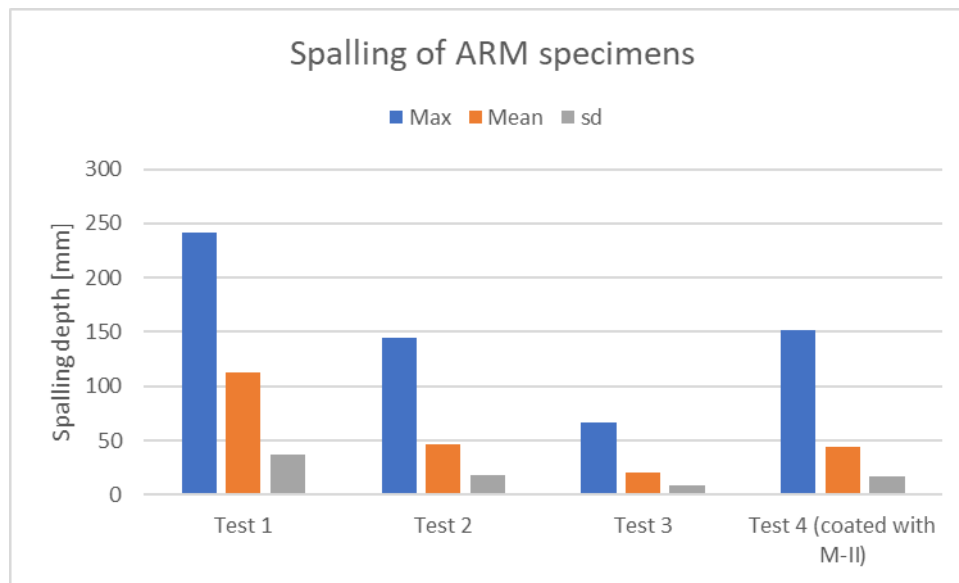


Figure 4-19: Measured maximum and mean spalling depth of ordinary reinforced concrete specimens.

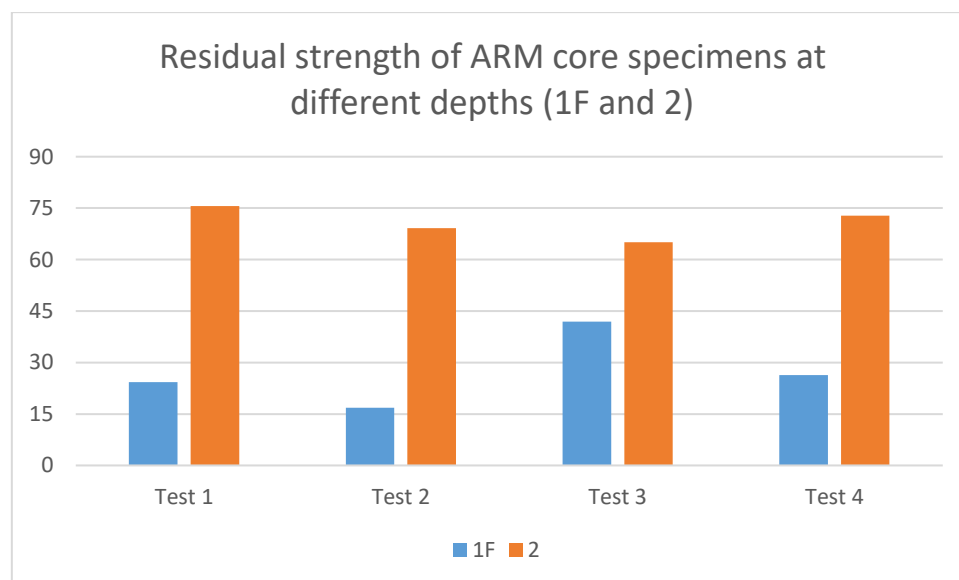


Figure 4-20: Residual strength of ARM core specimens at different depths (1F and 2).

The results presented in Figure 4-20 illustrate the variation of compressive strength with depth for the ARM specimens. A consistent increase in strength is observed from the fire-exposed region (1F) to the inner region (2) across all specimens. The near-surface cores exhibit significantly reduced strength, particularly in ARM2, indicating severe local damage due to thermal exposure. In contrast, the inner cores retain substantially higher strength, confirming that the effects of fire are largely confined to the outer layer. Notably, ARM3 shows a comparatively higher strength in the exposed region, highlighting the non-uniform and localized nature of fire-induced damage.

4.3.2 Influence of fire-protective coating on spalling behaviour

Specimen ARM 4 was coated with a fire-protective spray layer prior to testing. Such coatings belong to the family of spray-applied fire-resistive materials (SFRMs), which are widely used as passive fire protection systems in buildings and infrastructure. These materials typically possess low thermal conductivity and act as insulating barriers that delay heat transfer into the protected structural element during fire exposure[49].

Cementitious SFRMs are commonly composed of Portland cement or gypsum binders combined with lightweight porous fillers such as vermiculite or perlite, which reduce thermal conductivity and improve fire insulation performance. One example of such materials is Fendolite M-II that was used for current study, a high-density SFRM with typical densities around 700 kg/m³ and significant mechanical strength.

The presence of such a protective layer can reduce the rate of temperature increase in the underlying concrete and moderate the development of thermal gradients[49]. Consequently, the conditions promoting explosive spalling, such as rapid vaporization of pore water and thermally induced stresses may be reduced.

The influence of this protective coating can be observed in the temperature development recorded by the thermocouples embedded in the specimens. At the thermocouple located 5 cm from the exposed surface, the coated specimen exhibited a significantly slower temperature increase compared to most untreated ARM specimens. For instance, the temperature of 100 °C was reached after approximately 72 minutes in coated specimen, whereas it was reached after only 24–25 minutes in untreated specimens. Similarly, the time required to reach 250 °C and 500 °C was considerably longer in ARM4. This delayed heating behaviour indicates that the protective spray layer reduced the heat flux in the near-surface region.

From a physical perspective, the observed delay in temperature rise is consistent with the expected behaviour of spray-applied fire-resistive materials. By introducing an additional insulating layer, the protective coating reduces the rate of heat transfer into the underlying concrete[49].

The spalling results observed for ARM4 appear broadly consistent with this thermal behaviour. The coated specimen seemed to have lower on average maximum spalling values, as seen on Fig.4-20, although it did not show the lowest spalling severity within the ARM group. Moreover, on Fig. 4-21, the application of M-II appears to have reduced the extent of deep, severe spalling and shifted the damage distribution toward more moderate spalling depths. This observation suggests that the presence of the protective spray may have contributed to mitigating the severity of fire-induced damage by delaying heat penetration into the concrete substrate.

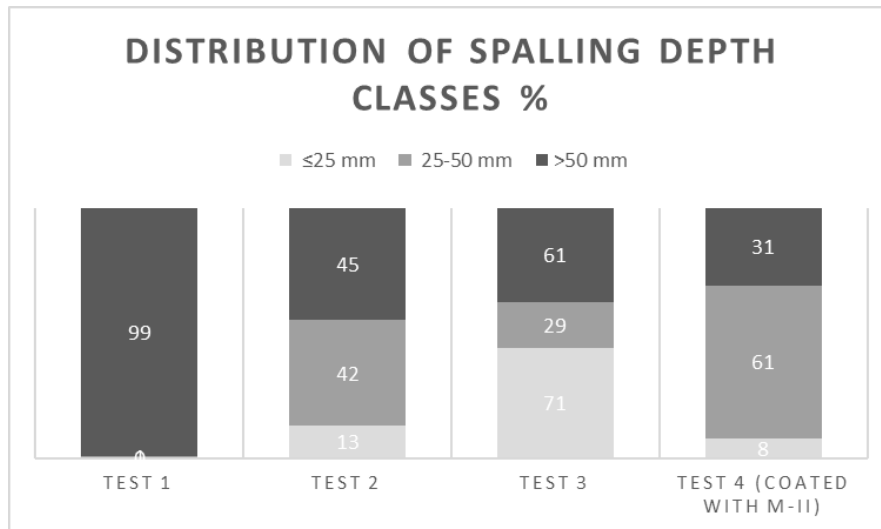


Figure 4-21: Distribution of spalling depth classes across the exposed surface for ARM groups. Percentages are calculated based on the ratio of surface points within defined material loss intervals (initial thickness = 300 mm).

Since only one fire-protected specimen was assessed in this experimental campaign, it is difficult to attribute the improved performance to SFRM with certainty.

4.3.3 Analysis of spalling behaviour of Steel Fibre Reinforced specimens

Steel-fiber-reinforced concrete (SFRC) consists of a cementitious matrix incorporating randomly distributed steel fibres, which are primarily intended to enhance tensile strength, ductility, and crack-control capacity. In fire conditions, these characteristics become particularly important, since explosive spalling is closely associated with the development of pore pressure and thermally induced stresses within the concrete[50].

According to the reviewed literature[51], [52], SFRC generally exhibits better residual mechanical performance than plain concrete and, in many cases, a lower tendency to explosive spalling. This beneficial behaviour is mainly attributed to the crack-bridging action of steel fibres, their contribution to residual tensile strength, and their ability to promote a more uniform heat transfer through the material, thereby reducing thermal gradients and delaying crack propagation. In addition, steel fibres may help mitigate the accumulation of internal steam pressure during heating.

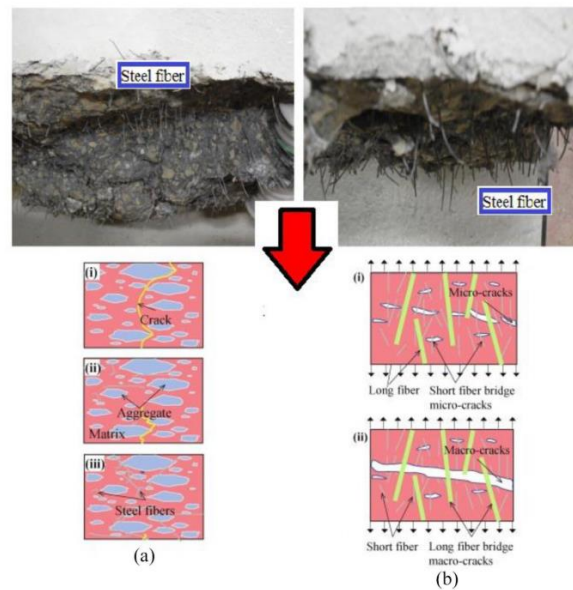


Figure 4-22[53]: The mechanism of SFRC to prevent crack propagation (a) contents, and (b) geometry.

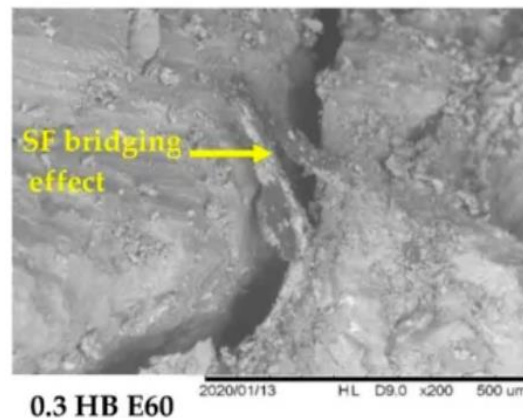


Figure 4-23[54]: Bridging effect of steel fibres in concrete.

However, there is conflicting findings and opinions about the extent of steel fibre's role in mitigation of explosive spalling. Some researches [55] [45] have reported reduced risk of explosive spalling due to improved pore pressure built-up resistance. Moreover, because of its higher thermal conductivity compared to aggregates or cement substrates, it allows to more even heat transfer within the element, therefore reducing the thermal gradient stresses[56].

This behaviour was also reported in this study, where thermocouples in FRC specimens at 10 cm and 15 cm depth from the exposed surface reached temperature milestones significantly earlier than that of specimens without fibres. This suggests a more effective transfer of heat into the interior of the steel-fibre-reinforced concrete, resulting in a less pronounced thermal gradient through the section.

On the contrary, some researchers [57], [58] have found that steel fibres do not completely eliminate the risk of spalling.

At the microstructural level, steel fibres influence the cracking and pore structure of heated concrete. Compared with ordinary concrete, SFRC tends to develop a higher density of smaller microcracks rather than a few large cracks, resulting in a more distributed damage pattern[45].

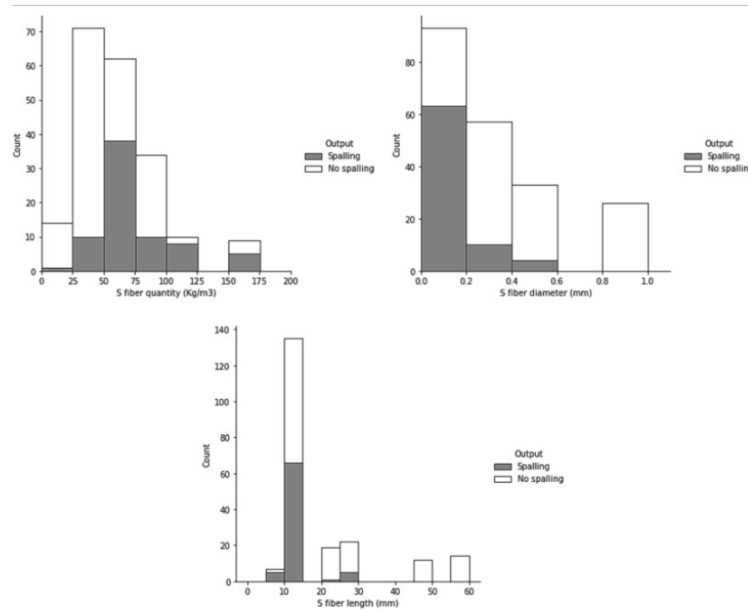


Figure 4-24[59]: Distribution of spalling occurrence in relation to steel fibre dosage and geometric characteristics (fibre length and diameter) based on the compiled experimental dataset.

It is important to take into account geometrical and quantitate parameters when assessing the effectiveness of inclusion of fibres for spalling mitigation. The study that summarised experimental results across the research field on spalling[59], highlights that in general, SFRC specimens exhibited lower spalling rates (10–22%), except at fibre dosages of 50–75 kg/m³ and above 100 kg/m³, where spalling increased. As shown in Fig.4-24, larger steel fibres were associated with fewer spalled specimens compared to smaller fibres.

When we compare SFRC specimens with specimens without fibres (ARM) in terms of material loss, slightly lower values of maximum spalling depth (~7%) and volume loss (~5%) is measured. In addition, FRC specimens exhibited less varied and predictable results within the group compared to ARM. It can be concluded that, while showing more homogenous and slightly less damage, they didn't improve material retainment significantly compared to ordinary specimens. Depth loss measured across all tested FRC specimens is visualised in Fig.4-25.

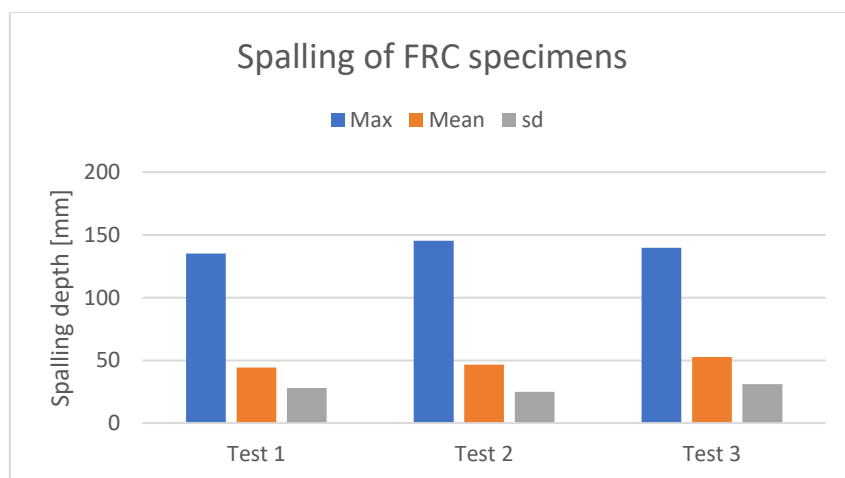


Figure 4-25: Measured maximum and mean spalling depth of steel fibre reinforced concrete specimens.

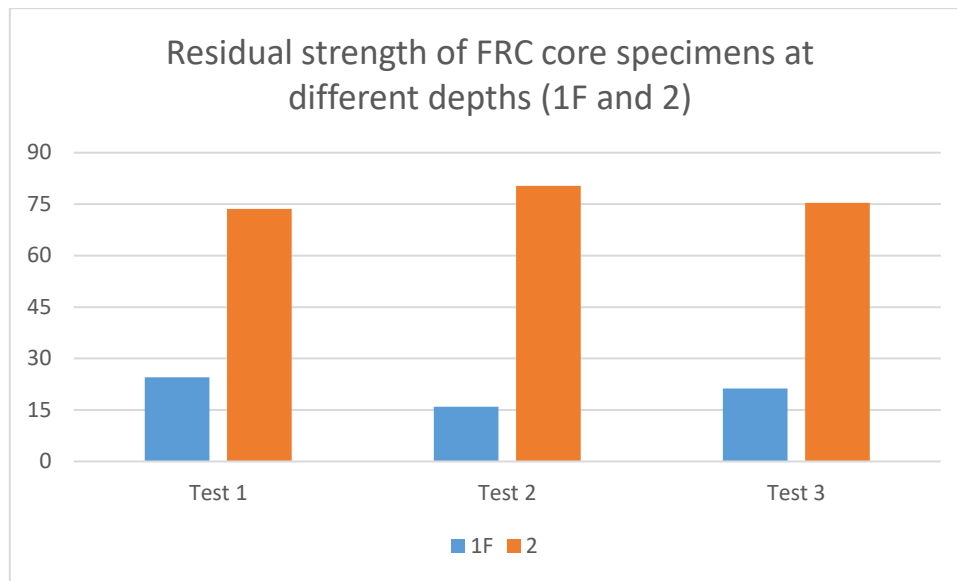


Figure 4-26: Residual strength of FRC core specimens at different depths (1F and 2).

Figure 4-26 presents the residual compressive strength of FRC core specimens at different depths. Similar to the ARM specimens, a clear increase in strength is observed from the fire-exposed region (1F) to the inner region (2), confirming that thermal damage is primarily concentrated near the exposed surface. However, compared to ARM, the FRC specimens exhibit consistently lower compressive strength in the 1F region, with values ranging from approximately 15.9 MPa to 24.5 MPa, whereas ARM specimens showed higher and more scattered values. This indicates that, despite the presence of fibres, FRC does not provide a clear advantage in terms of residual compressive strength under severe thermal exposure.

It is important to note that the difference in water-to-cement ratio between ARM (0.42) and FRC (0.35) is significant enough to affect the microstructure and transport properties of the concrete. The lower w/c ratio of FRC likely produced a denser and less permeable matrix, which may have contributed to different thermal and spalling behaviour under fire exposure. However, this effect should be interpreted together with the influence of fibre addition and other differences in mix composition.

4.3.4 Analysis of spalling behaviour of Polypropylene-modified specimens

The polypropylene-modified specimens exhibited noticeably different spalling behaviour compared to the ordinary reinforced concrete specimens. On average, PP-modified specimens showed reduced severity of damage: around 45% reduction in maximum spalling depth and up to 20% reduction in volume loss. Moreover, in most cases, the observed damage was more gradual, with smaller surface detachments rather than large fragments being violently expelled from the exposed face. As was seen previously (Fig.4-13), PP specimens experienced only about 15% of mean depth loss more than 5cm into the exposed face, compared to ARM specimens (around 53%), which shows more resistant behaviour to large material detachments.

Fig.4-27 highlights that the gap between values measured for maximum and mean spalling depth is noticeably smaller than that of ARM specimens. This further confirms more uniform spalling behaviour compared to concrete without fibres.

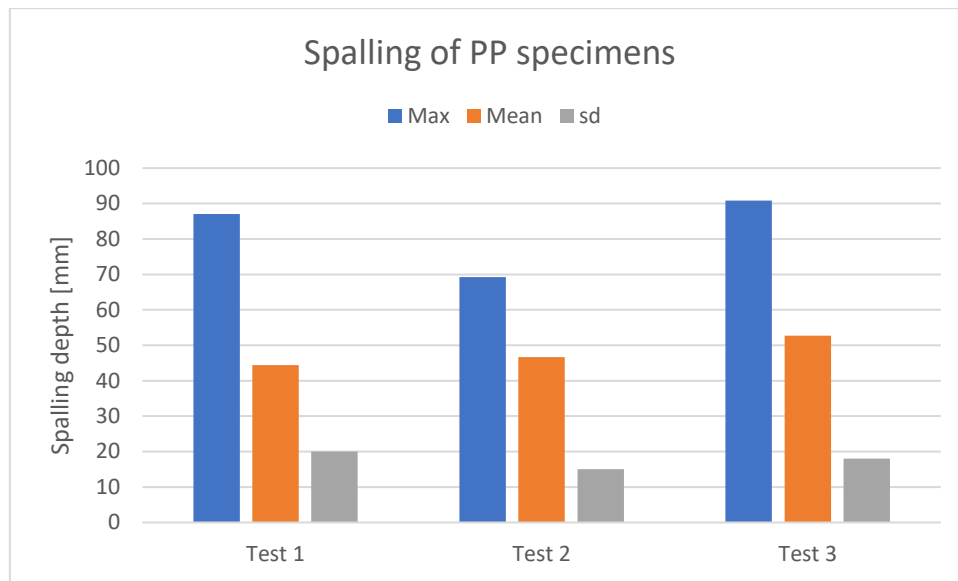


Figure 4-27: Measured maximum and mean spalling depth of polypropylene fibre reinforced concrete specimens.

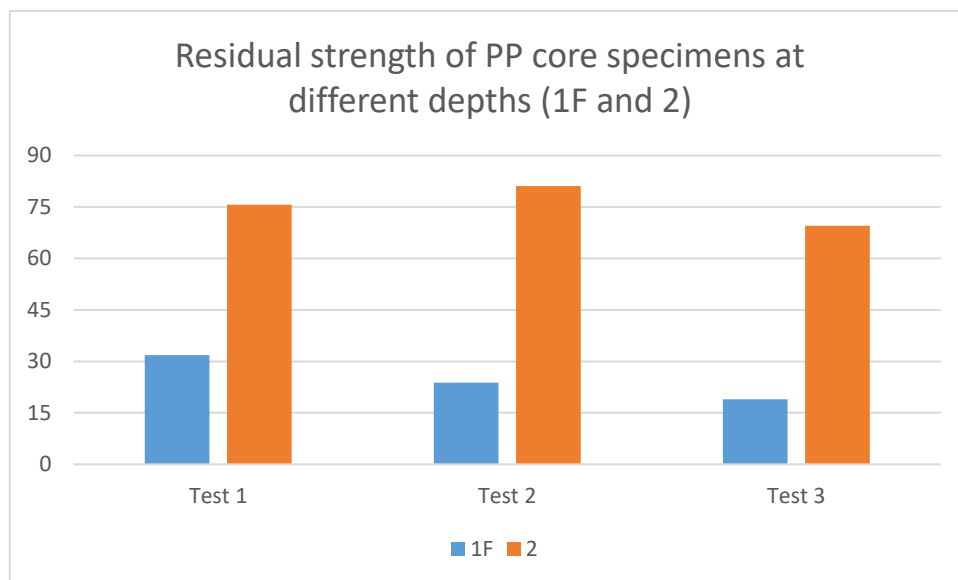


Figure 4-28: Residual strength of PP core specimens at different depths (1F and 2).

Figure 4-28 shows the residual compressive strength of PP core specimens at different depths. As observed for ARM and FRC, a clear increase in strength is evident from the fire-exposed region (1F) to the inner region (2), confirming that thermal damage is concentrated near the exposed surface. In the 1F region, PP specimens exhibit compressive strength values between 19.0 MPa and 31.8 MPa, which are generally higher than those of FRC and comparable to, or slightly lower than, the unprotected ARM specimens. This indicates a moderate improvement in residual strength near the exposed surface compared to FRC.

In the inner region (2), PP specimens exhibit compressive strength values similar to both ARM and FRC, indicating that the influence of polypropylene fibres becomes negligible where thermal exposure is less severe. Overall, the results suggest that PP fibres are effective in mitigating damage in the fire-exposed zone, while having limited impact on the mechanical properties of concrete in regions unaffected by high temperatures.

This trend can also be seen in temperature development within the specimens during fire exposure. Surface levelled thermocouples (5 cm from exposed face) of most specimens reached much lower temperature peaks by the end of the test (around 550 °C) and showed better heat transfer than blocks without fibres, similarly to SFRC specimens. Therefore, fibres could have reduced internal stresses acting on concrete cross section induced by thermal gradient.

The influence of synthetic fibres has been studied extensively in recent years. When exposed to elevated temperatures, PP fibres undergo noticeable changes. At around 105°C, dimensional changes PP fibres experience (around 41 times greater than cement base) leads to radial microcracks in concrete matrix [60]. Furthermore, PP fibres have low melting temperature of 165°C, which entails that in higher temperatures the fibres melt and disappear which creates vacant channels. This behaviour paired with microcracks induced by dimensional changes at earlier stages of heating results in interconnected network of empty channel, thus allowing easier vapor migration and lower pore pressure within concrete.

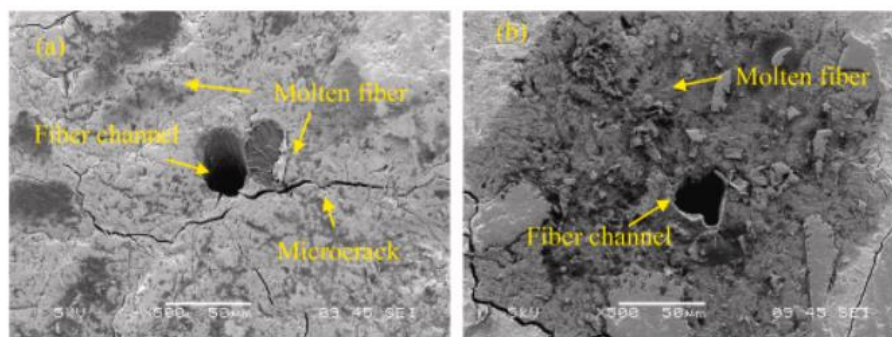


Figure 4-29[60]: Micrographs of PP modified specimen after exposure to 200°C.

Since built-up pore pressure is widely accepted as primary cause of explosive spalling, Ding et al [46] conducted an experimental campaign to analyse pressure changes within concrete beams with varied composition exposed to elevated temperature. Fig. 4-30 illustrates about 50% lower values of pore pressure in PP modified beam (Fig.4-30. b) compared to concrete without fibres (Fig.4-30. a). Although, SFRC exhibits slightly lower pore pressure, the effect of steel fibres is not as significant as polypropylene fibres. Moreover, beam made up of both steel and polypropylene fibres as in current study (Fig-30. e) demonstrates even better resistance to pore built up pressure. This could be explained as that different mechanisms of steel and pp fibres during heating act together and improve moisture transport and thus better resistance to spalling.

It is worth to highlight that compared to ordinary concrete, the descending branch of pore pressure-time curve of FRC drops more severely. This is likely due to the pore pressure reduction effect of fibres via the introduction of network of microcracks[46].

The incorporation of fibres can delay the time at which peak pore pressure develops at various depths within the concrete[46]. This behaviour can be explained by the moisture clog theory[61]. During heating, pore pressure initially increases near the exposed surface. The resulting pressure gradient drives moisture toward the cooler inner regions of the concrete, where the vapour progressively condenses and forms a saturated zone, commonly referred to as a moisture clog. This saturated layer restricts further vapour migration, leading to a rapid buildup of pore pressure. However, the presence of numerous interfacial transition zones (ITZ) around the fibres increases the permeability of FRC, which limits the formation and

development of the moisture clog and consequently delays the occurrence of peak pore pressure.

This trend is further confirmed by the results of this experimental testing. In general, hybrid fibres (PP) significantly reduced material loss due to spalling, while specimens reinforced only with steel fibres did not show as big of an improvement in spalling behaviour.

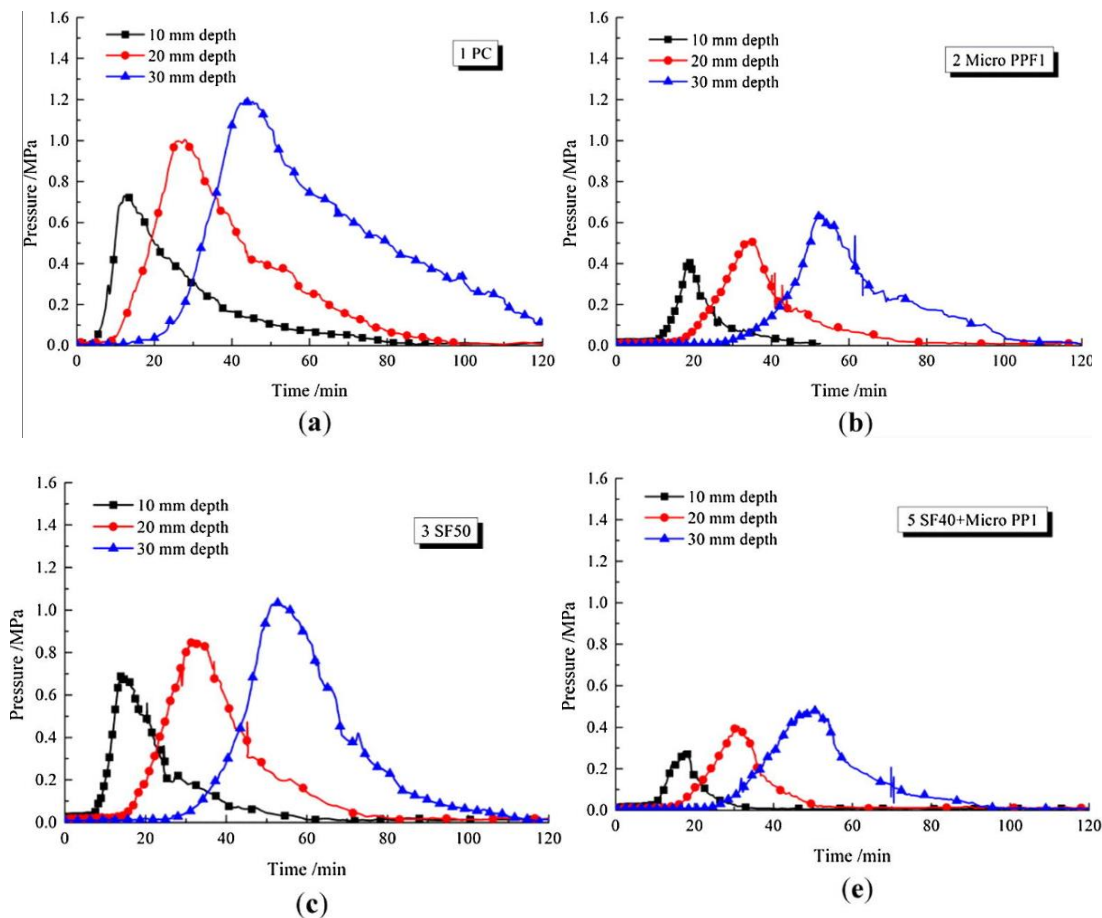


Figure 4-30[46]: Comparison of pore pressure-time curves of beams with or without fibers during fire exposure. (a) ordinary concrete; (b) Micro-propylene fibre added concrete; (c) Steel fibre reinforced concrete; (e) SFRC+PP modified concrete.

4.3.5 Influencing parameters on effectiveness of PP fibres against spalling

A broader analysis of experimental data available in the literature highlights the influence of PP fibre characteristics on spalling mitigation. Study conducted at Clemson University [59] compiled a statistical dataset of experimental campaigns on spalling, suggest a positive correlation between fibre length and spalling resistance, as longer fibres appear to reduce the likelihood of explosive spalling (Fig.4-31).

The cross-sectional size of PP fibres influences their ability to generate pressure-relief channels within the concrete matrix. Fibres with smaller cross-sections generally provide a higher number of fibres per unit volume, increasing the probability of forming interconnected

microcrack networks and improving vapor migration pathways. Consequently, smaller fibre diameters have been reported to reduce the propensity for explosive spalling[18].

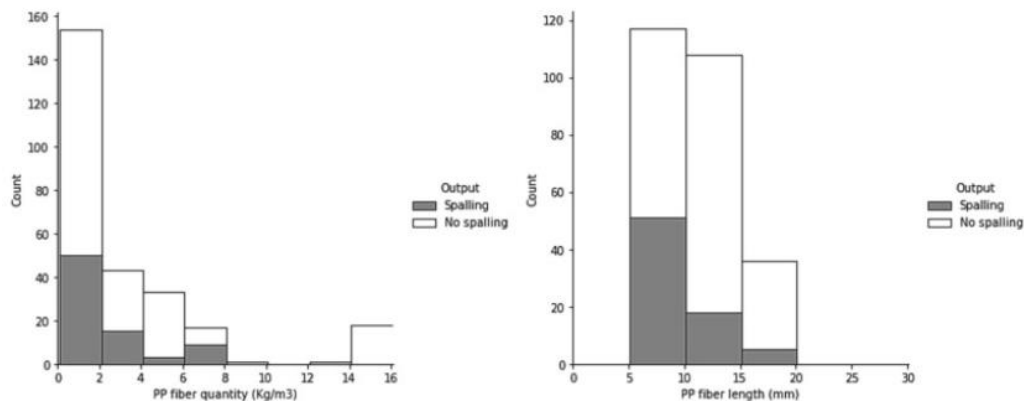


Figure 4-31[59]:Distribution of spalling occurrence in relation to PP fibre dosage and geometric characteristics (fibre length and diameter) based on the compiled experimental dataset.

The amount of PP fibres incorporated into the concrete mix strongly affects spalling mitigation. In general, higher fibre dosages tend to improve resistance to explosive spalling. However, experimental observations indicate that the relationship is not strictly linear. In some cases, relatively low fibre dosages ($\approx 0.7 \text{ kg/m}^3$) have proven effective, while higher dosages may not always provide additional benefits depending on fibre geometry and distribution[18].

Recent studies [18] suggest that the total surface area of PP fibres within the concrete matrix may be a more relevant parameter than fibre length or number alone. Mixes characterized by a large total fibre surface area and a high number of individual fibres tend to exhibit improved permeability after heating, facilitating vapor pressure release and reducing the likelihood of explosive spalling.

However, the inclusion of PP fibres may negatively affect the workability of the concrete, typically reducing slump flow. Fibres with smaller diameters or longer lengths tend to have a stronger influence on workability due to increased surface interaction with the cement paste.

5 CONCLUSION

Fire-induced spalling represents one of the most critical deterioration mechanisms affecting concrete structures exposed to elevated temperatures. The phenomenon can lead to severe material loss, reduction of the effective cross-section, and exposure of reinforcement, ultimately compromising structural safety. Understanding the mechanisms governing spalling and identifying effective mitigation strategies therefore remain important research topics in structural fire engineering.

The experimental investigation demonstrated that polypropylene (PP) fibre-modified concrete significantly outperformed ordinary reinforced concrete (ARM) and steel fibre-reinforced concrete (FRC) in resisting fire-induced spalling under ISO 834 exposure. PP specimens exhibited the lowest maximum spalling depths (average 82 mm), mean spalling depths (around 28 mm), and volume losses (average 8.6%), reducing severe damage (>50 mm loss) to less than 15% of the exposed surface. In contrast, ARM specimens showed high variability, with volume losses up to 37.4% and frequent reinforcement exposure, while FRC provided moderate improvements (average volume loss 15%) through crack-bridging but did not match PP efficacy.

Temperature profiles confirmed PP's benefits, with peak temperatures at 5 cm depth limited to ~550°C versus over 1000°C in ARM, due to enhanced permeability from melting fibres. Moreover, temperatures recorded at 10 and 15 cm depth showed that PP fibres enabled better heat transfer within concrete cross section, thus reducing the thermal gradient which is one of the key causes for spalling in concrete.

Figure 5-1 shows the relative maximum spalling depth demonstrated by each specimen group.

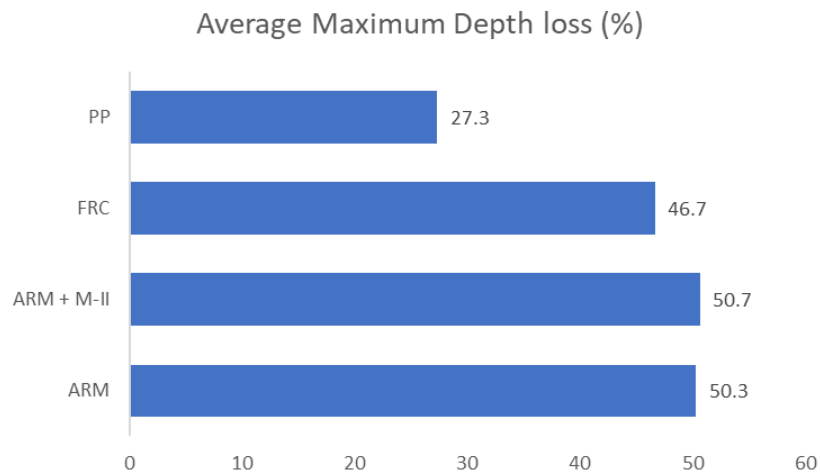


Figure 5-1: Average Maximum Depth loss of each group (% of 300 mm Specimen Thickness).

A similar trend appears when evaluating volume loss, where PP-modified concrete demonstrates the lowest material degradation.

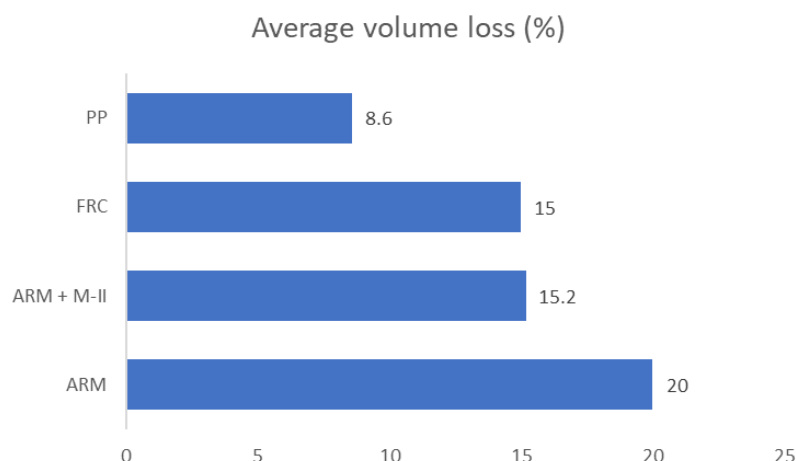


Figure 5-2: Average Volume loss of each group (%).

Table 5-1 compares the spalling performance of the investigated materials, where the reduction values for FRC and PP-FRC are expressed relative to the ordinary reinforced concrete (ARM) specimens. Polypropylene-modified specimens showed the lowest average maximum spalling depth, representing a reduction of approximately 45.5% compared to the ordinary reinforced concrete specimens (ARM).

Table 5-1: Performance Comparison of Ordinary RC vs FRC specimens.

Material Type	Max Spalling Depth	Volume Loss	Mechanism
ARM (Ordinary RC)	Up to 241 mm	Up to 37%	Low permeability → high pore pressure
FRC (Steel Fibres)	~7% reduction	~25% reduction	Crack bridging
PP-FRC (Polypropylene)	~45% reduction	~57% reduction	Fibre melting → pressure release

These results validate PP fibres' role in creating vapor escape channels, mitigating pore pressure buildup, the primary spalling driver that aligns with Eurocode recommendations for high-strength concretes. For practical applications like tunnels or high-rises, PP addition (1.5 kg/m³ micro-fibres) offers reliable passive protection, outperforming coatings (e.g., ARM4's 15.2% loss) in consistency. FRC's stability suits ductility-focused designs, but PP hybrids optimize fire safety without compromising strength.

The analysis of residual compressive strength further confirmed the localized nature of fire-induced damage. Core specimens extracted near the exposed surface retained only approximately 25–40% of the strength measured in the inner region, corresponding to a strength loss of up to 70%. In contrast, cores taken from deeper regions preserved most of their mechanical capacity, with compressive strength values remaining in the range of 65–80 MPa across all mixes. While differences between concrete compositions were generally

limited, PP-modified specimens showed slightly improved performance in the fire-exposed zone, whereas FRC did not demonstrate a clear advantage over ordinary concrete in terms of residual compressive strength. It is, however, important to note that the results are sensitive to specimen variability: excluding the highest value within each group leads to a noticeable reduction in the average strength of ARM specimens in the exposed region, resulting in values comparable to FRC, while PP exhibits the highest average among the mixes. This highlights the heterogeneous nature of fire-induced damage and indicates that the observed differences should be interpreted as indicative trends rather than definitive rankings of material performance. Overall, the results confirm that thermal gradients and damage localization govern the residual mechanical performance more significantly than mix composition.

Despite the limitations discussed throughout this study, several meaningful conclusions can be drawn from the experimental results. The inherently stochastic nature of fire-induced spalling introduce uncertainty in the quantitative comparison of results. In addition, parameters such as pore pressure and moisture migration were not directly measured, and only one specimen with fire-protective coating was available for analysis. Nevertheless, the experimental observations clearly demonstrate consistent trends among the investigated materials. Ordinary reinforced concrete specimens exhibited the most severe spalling damage, while steel fibre reinforced concrete showed moderate improvement in crack control. The most significant enhancement was observed in the polypropylene-modified specimens, which experienced substantially lower spalling depths and volume loss. These results confirm that the inclusion of polypropylene fibres improves permeability during heating and effectively mitigates explosive spalling in concrete exposed to fire.

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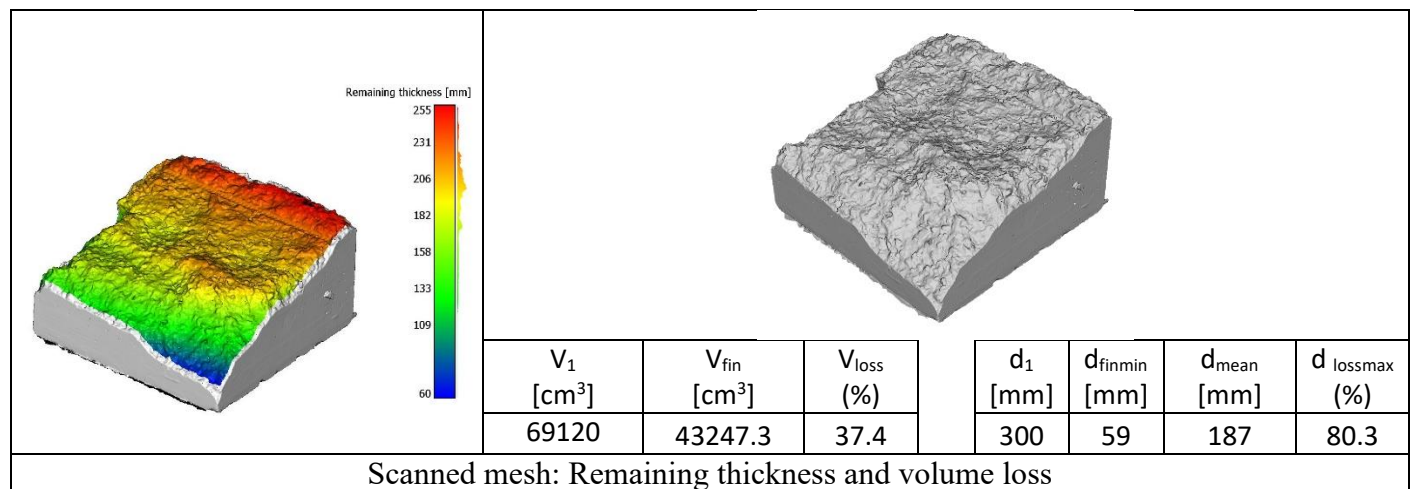
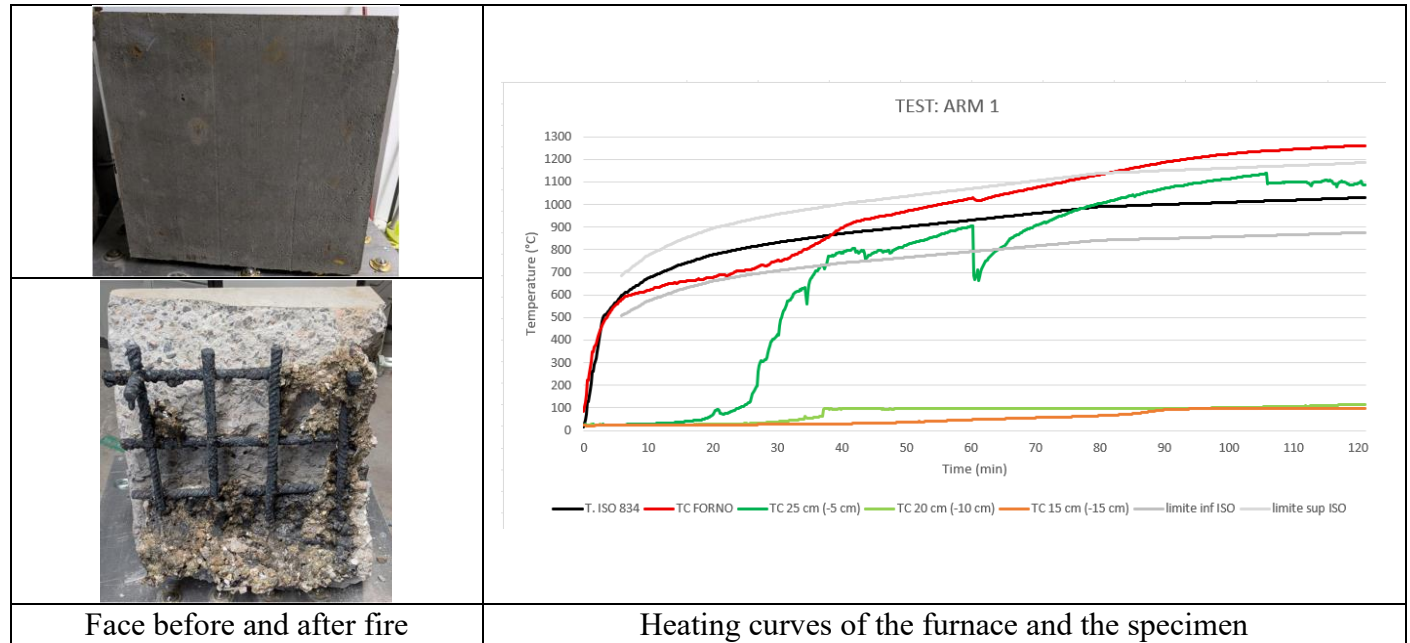
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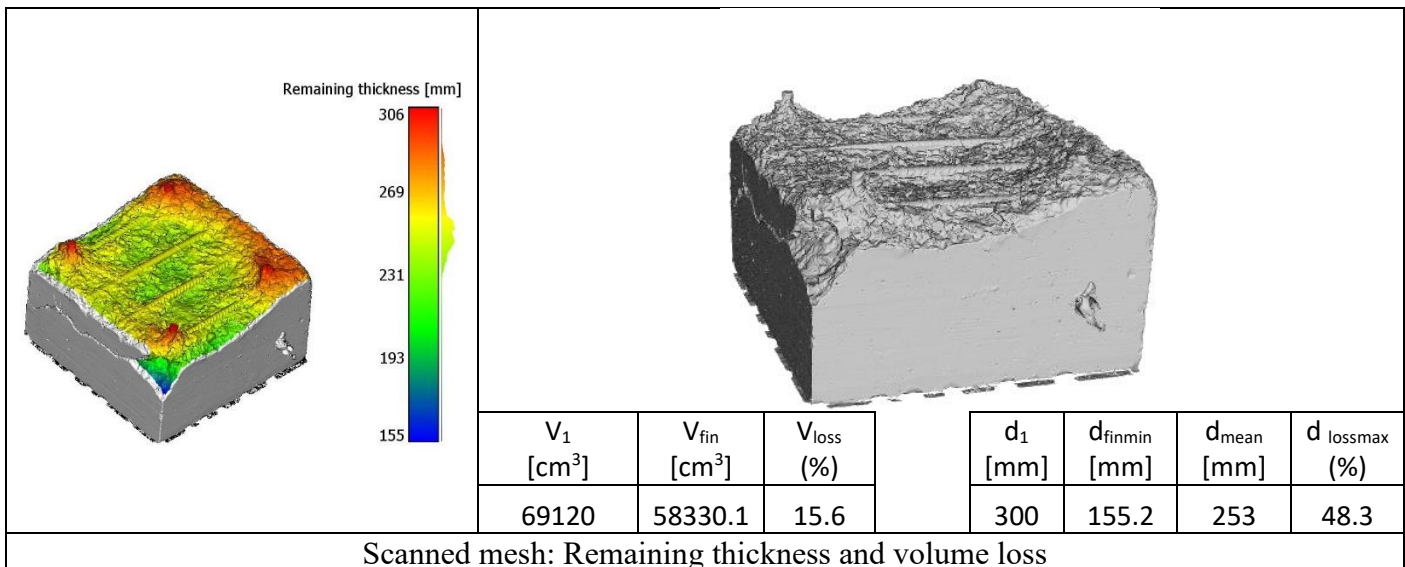
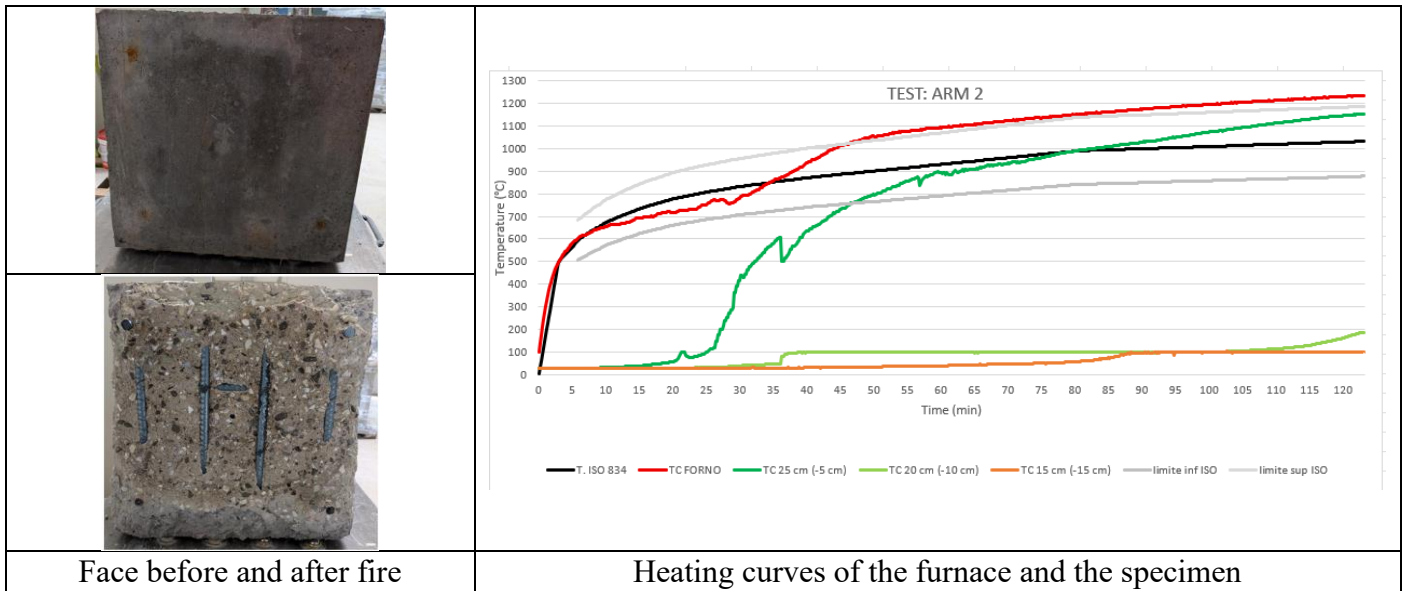
APPENDIX A

DETAILED EXPERIMENTAL RESULTS

Test: ARM 1

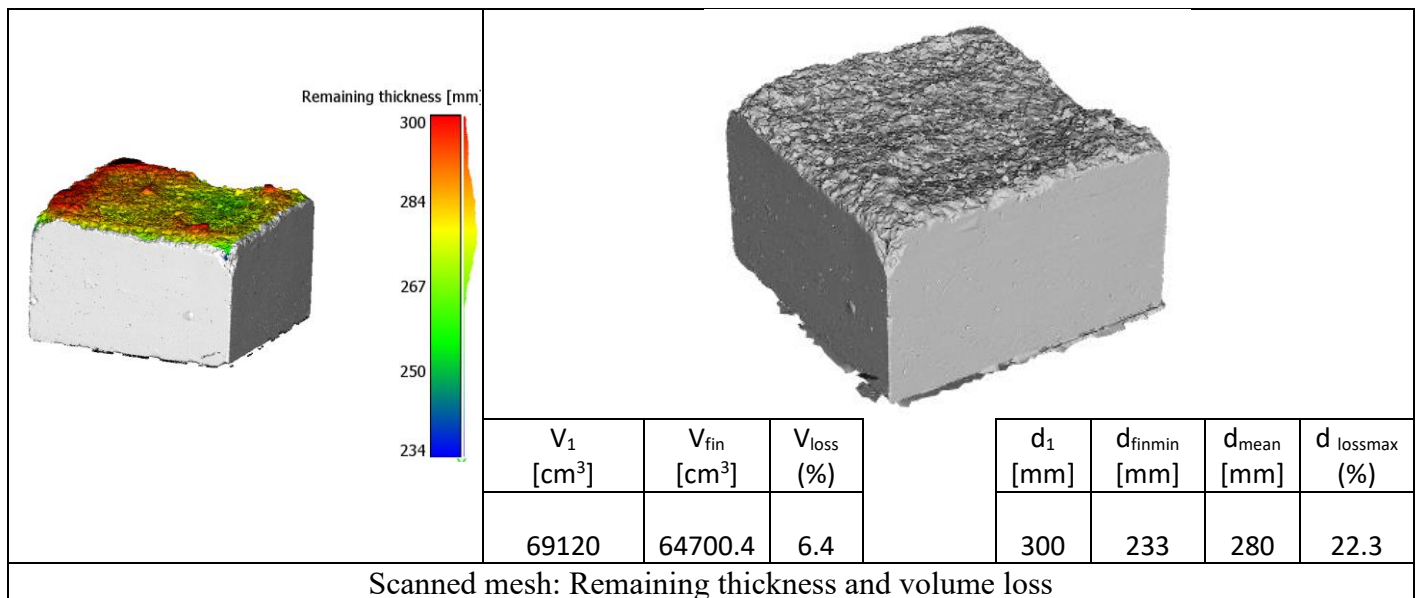
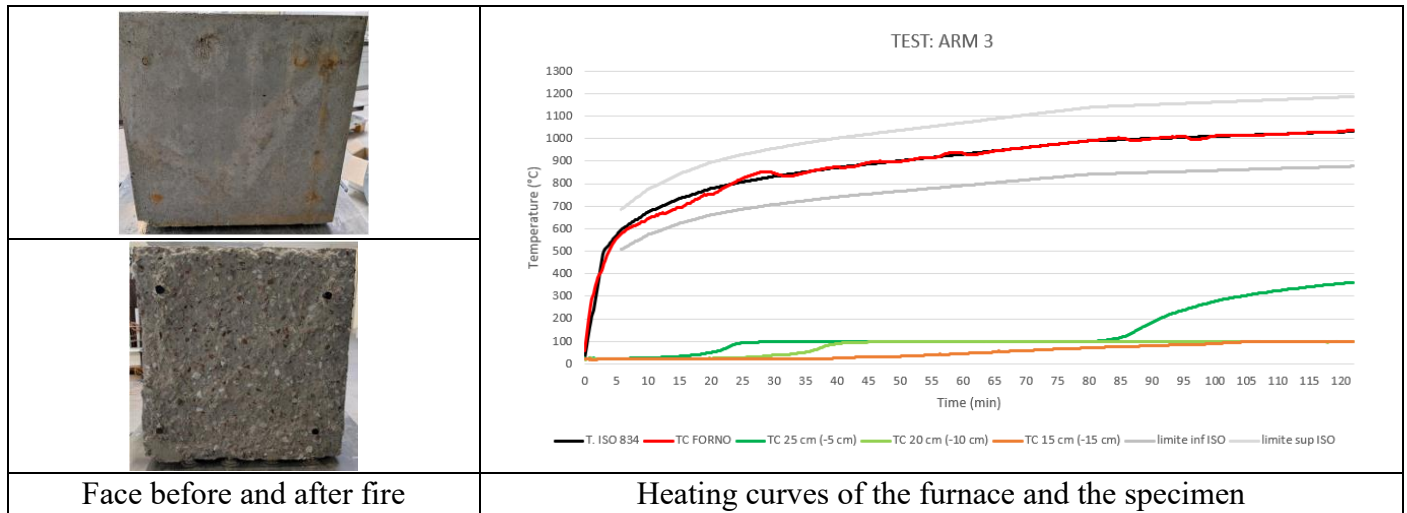


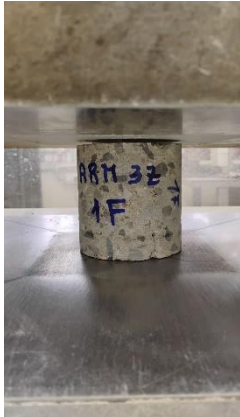
			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	fc (MPa)	Density(kg/m ³)	F c (MPa)

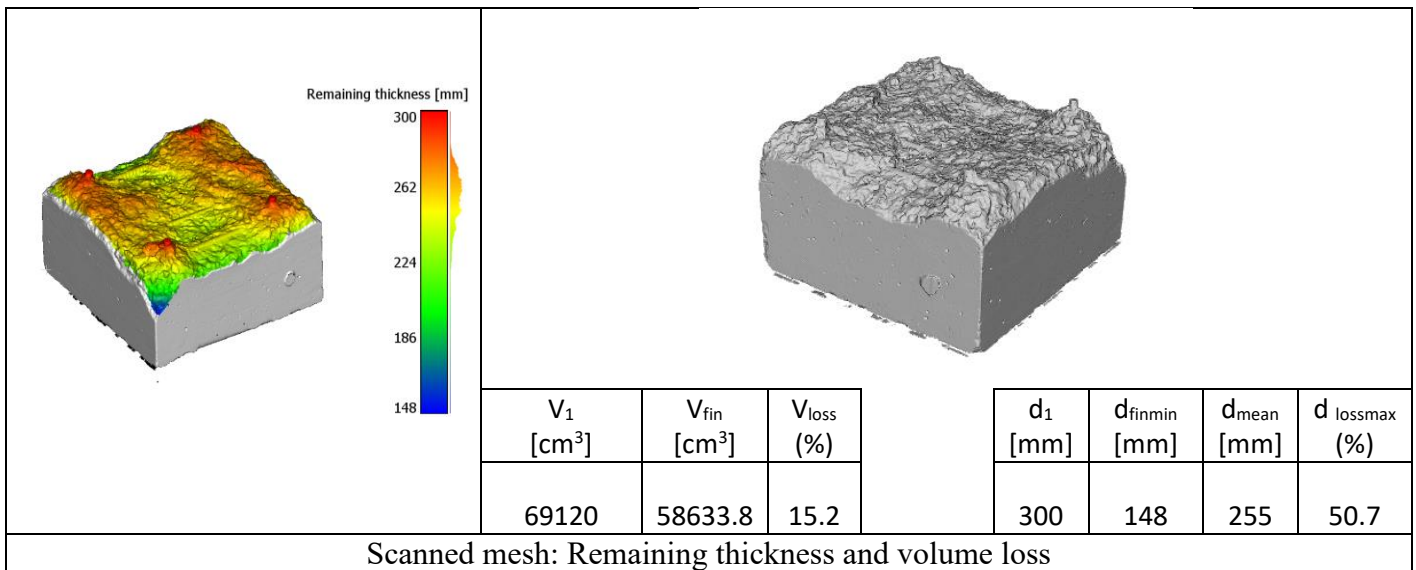
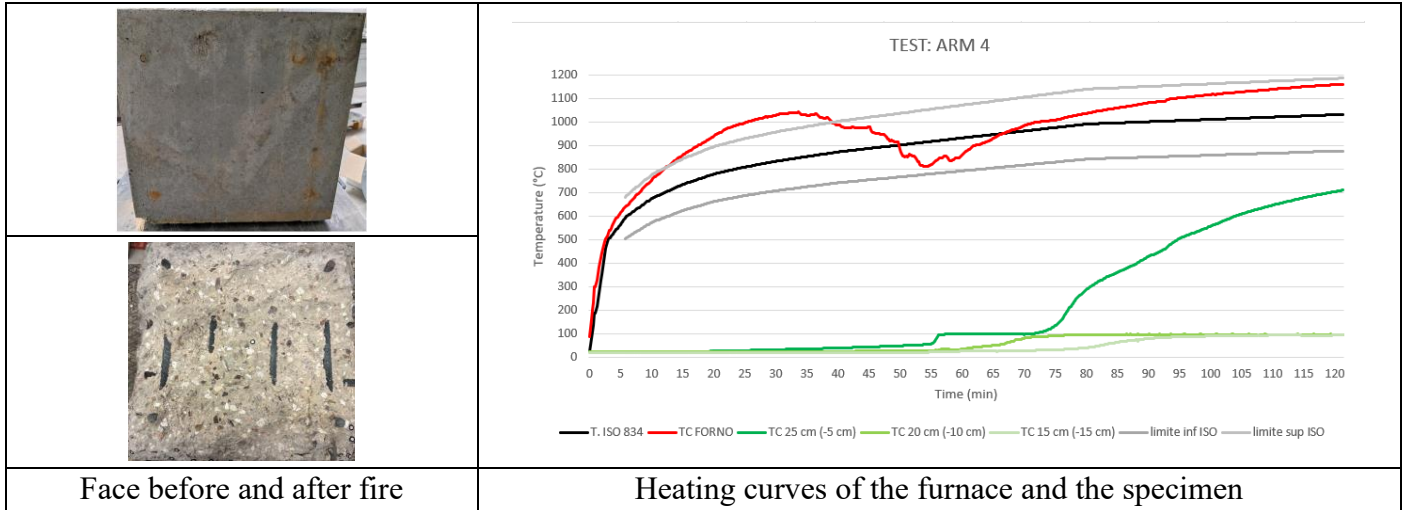


			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	f _c (MPa)	Density(kg/m ³)	F _c (MPa)
2236	16.8	2351	69.2
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

Test: ARM 3

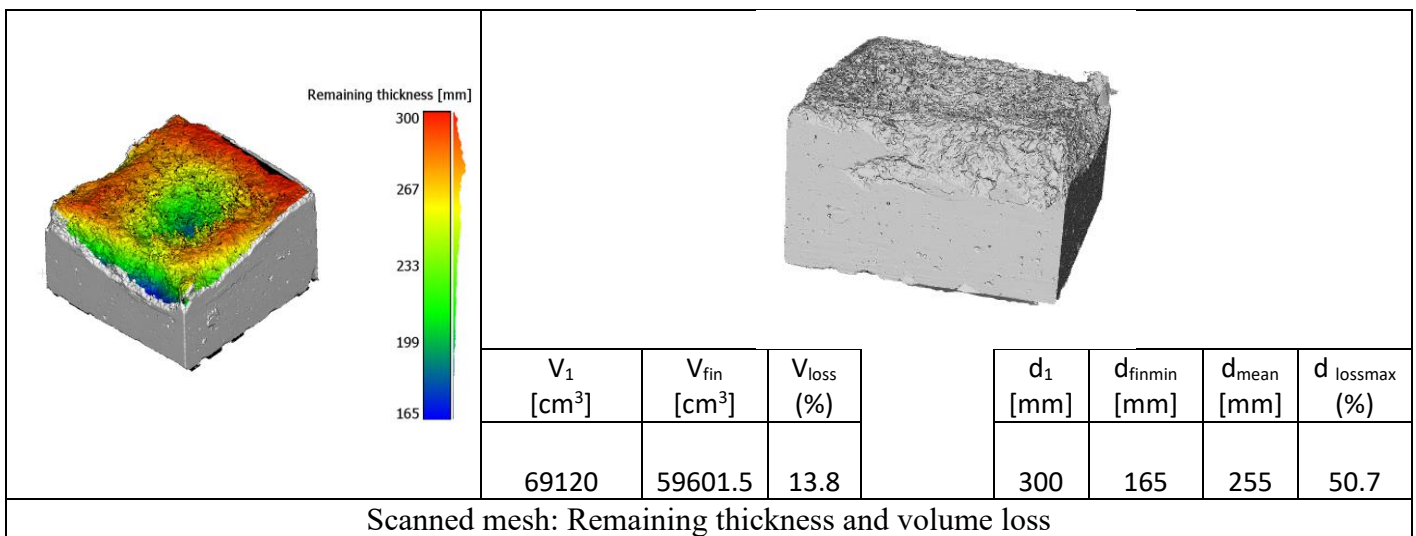
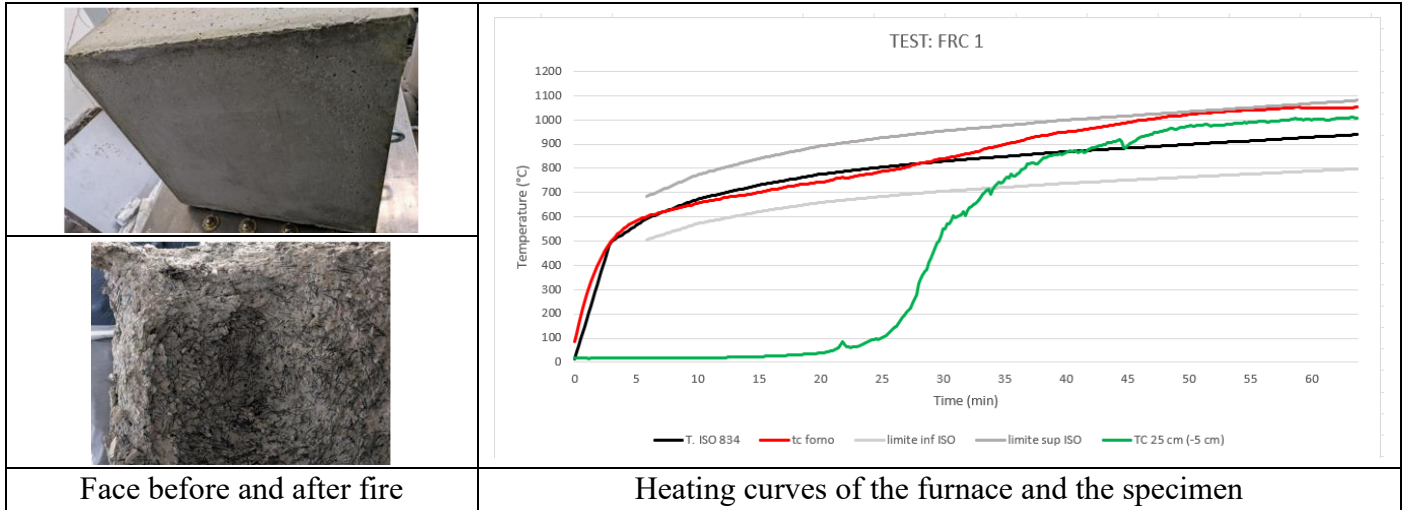


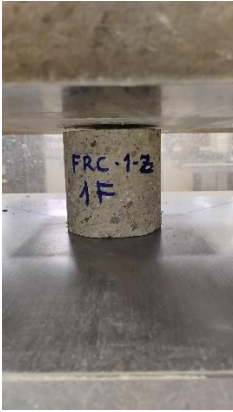
			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	f_c (MPa)	Density(kg/m ³)	F_c (MPa)
2301	41.9	2345	65.1
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	



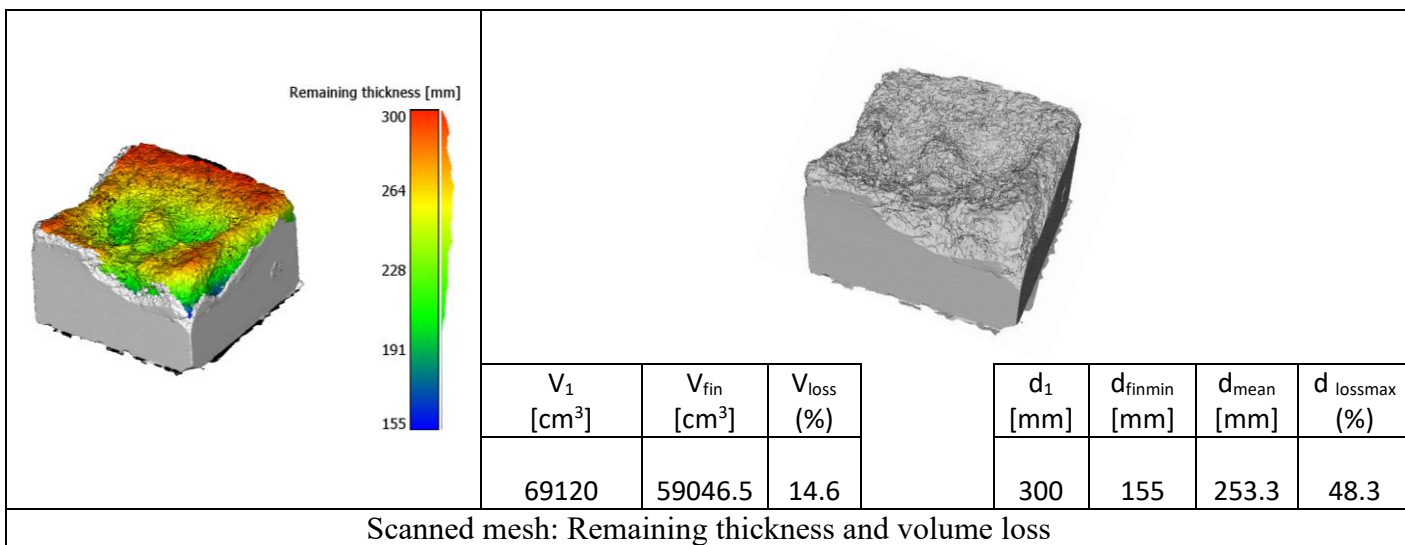
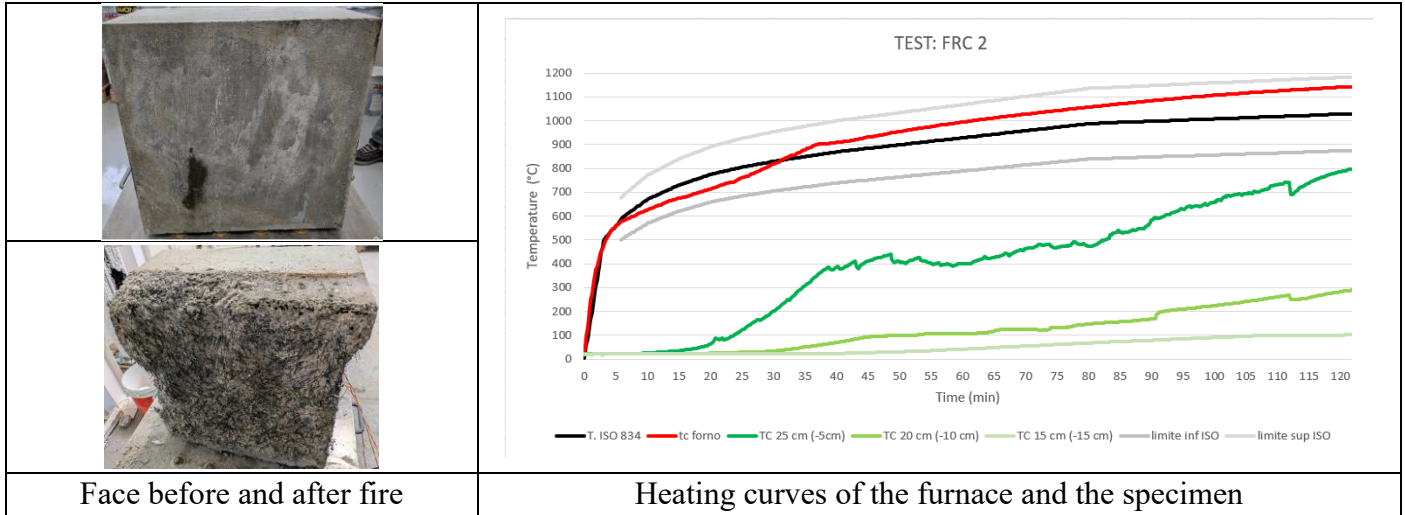
			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	f _c (MPa)	Density(kg/m ³)	F _c (MPa)
2274	26.3	2364	72.8
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

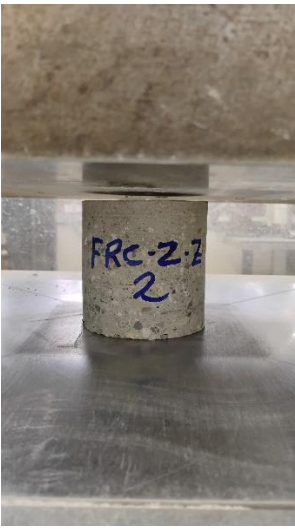
Test: FRC 1



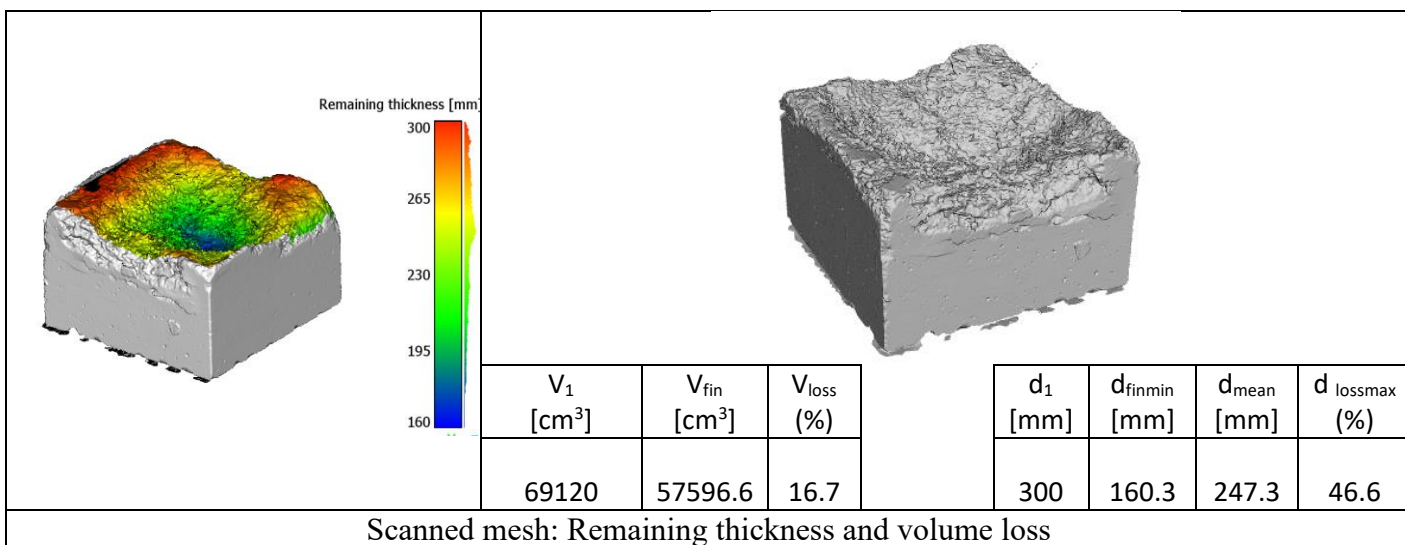
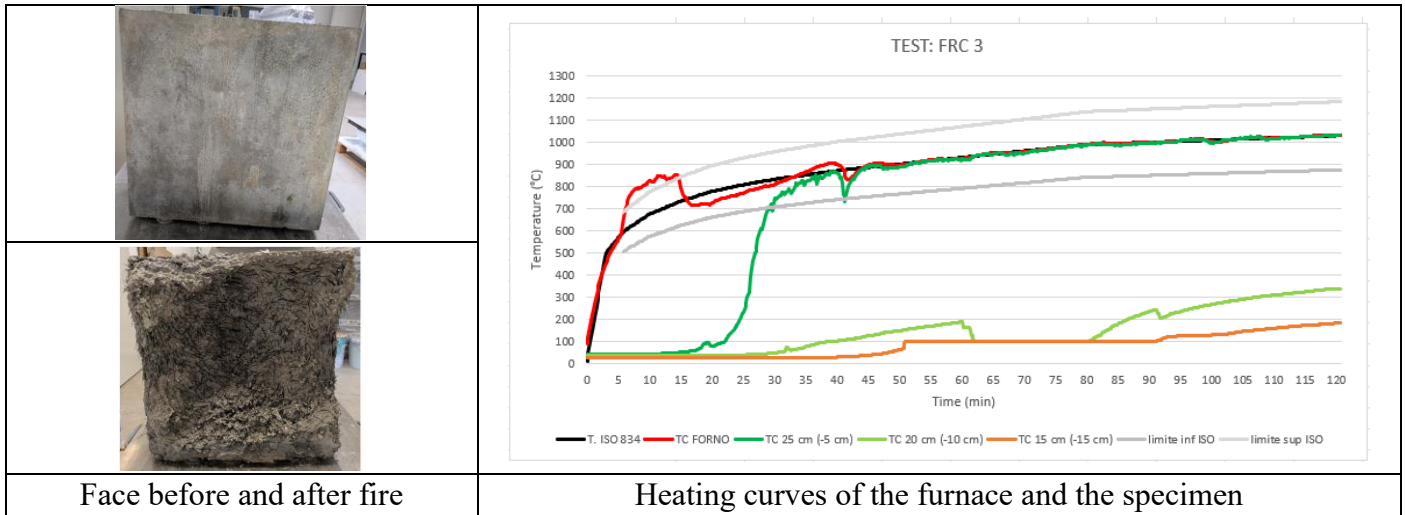
			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	f _c (MPa)	Density(kg/m ³)	F c (MPa)
2249	24.5	2328	73.6
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

Test: FRC 2



			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	fc (MPa)	Density(kg/m ³)	F c (MPa)
2251	15.9	2351	80.3
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

Test: FRC 3

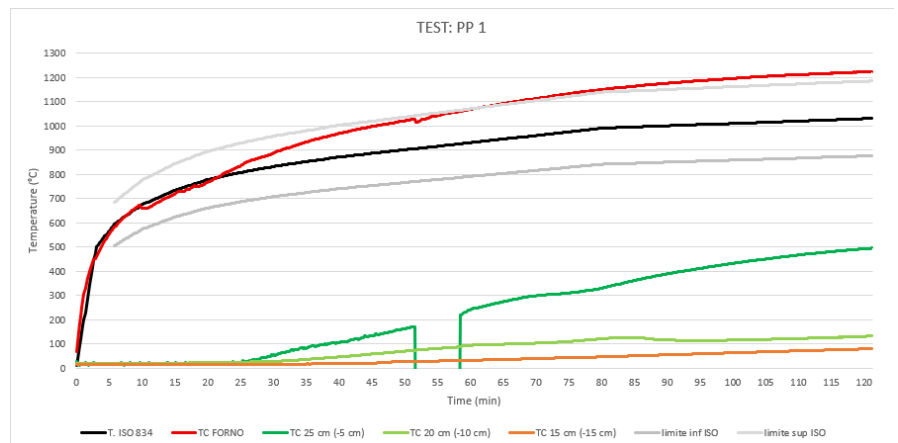


			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	f _c (MPa)	Density(kg/m ³)	F _c (MPa)
2241	21.3	2349	75.4
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

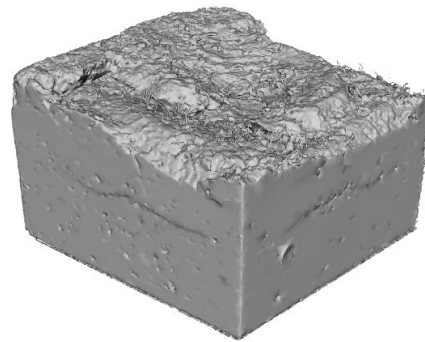
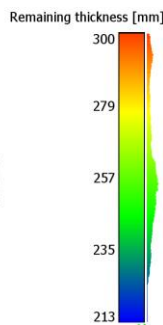
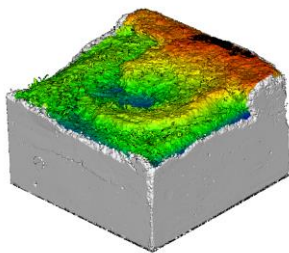
Test: PP 1



Face before and after fire

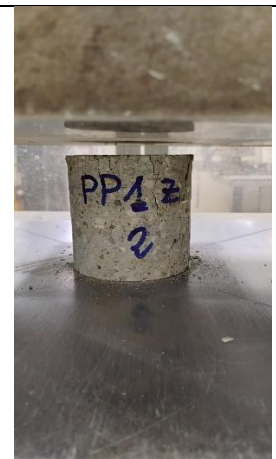
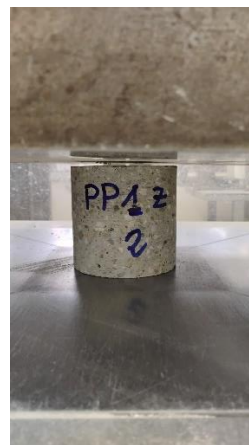
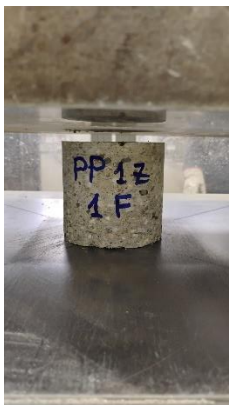


Heating curves of the furnace and the specimen



V_1 [cm ³]	V_{fin} [cm ³]	V_{loss} (%)	d_1 [mm]	d_{finmin} [mm]	d_{mean} [mm]	$d_{lossmax}$ (%)
69120	60136.9	13	300	213	261.3	29

Scanned mesh: Remaining thickness and volume loss



Before comp. test

After comp. test

Before comp. test

After comp. test

Density (kg/m³)

f_c (MPa)

Density(kg/m³)

F_c (MPa)

2238

31.8

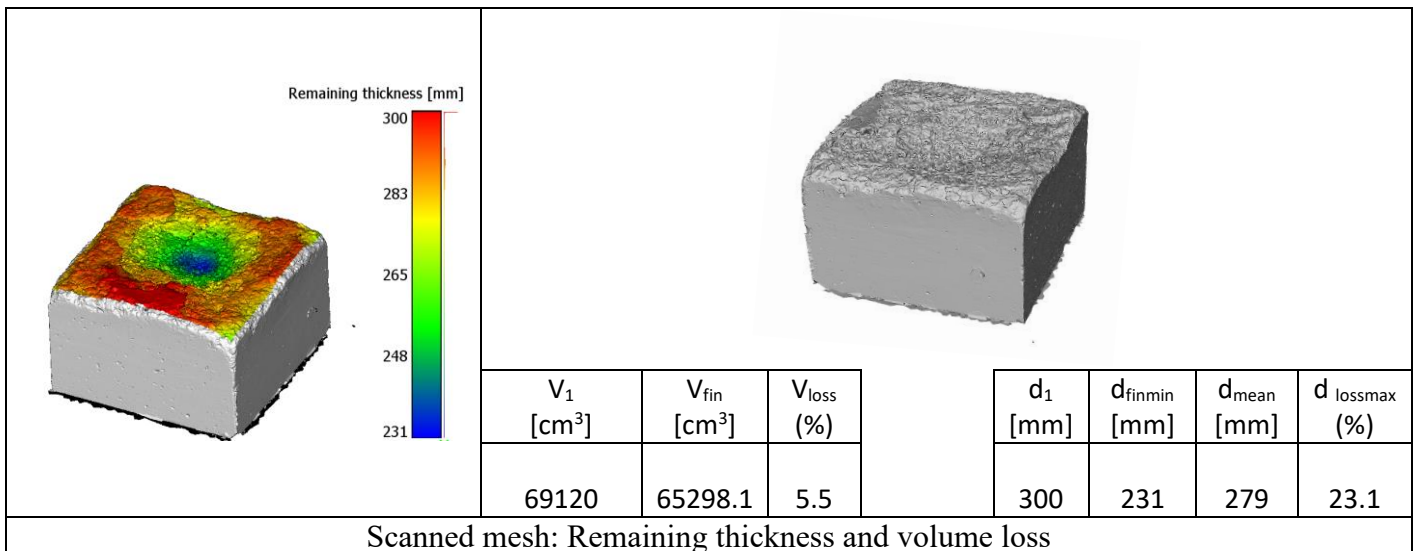
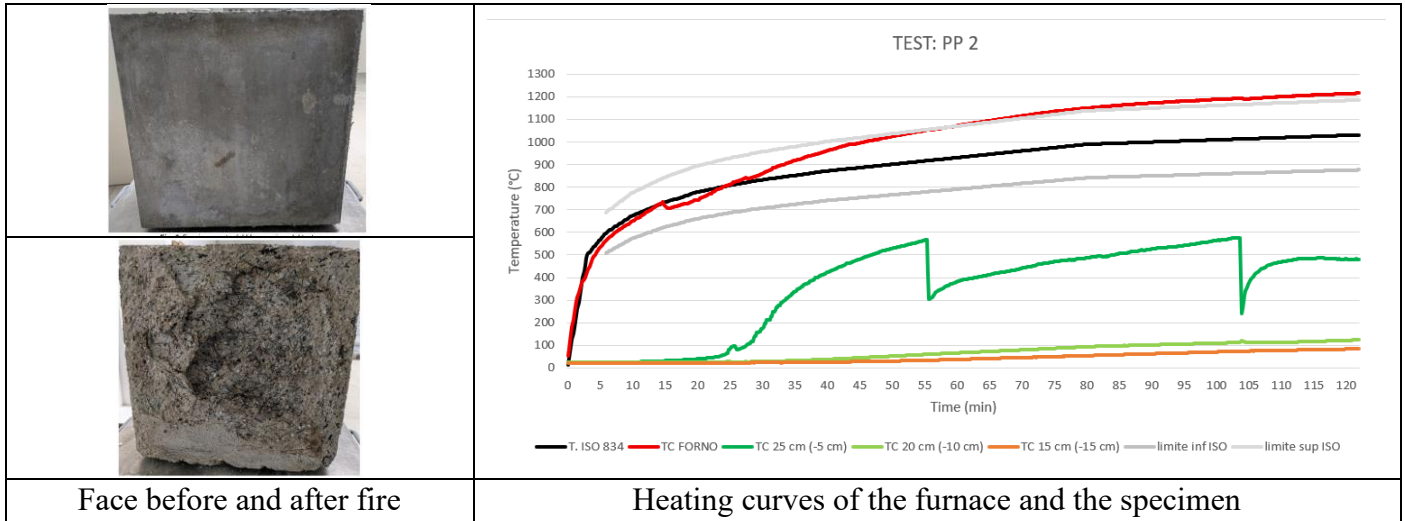
2321

75.7

Extracted core: 1F (near to fire exposed face)

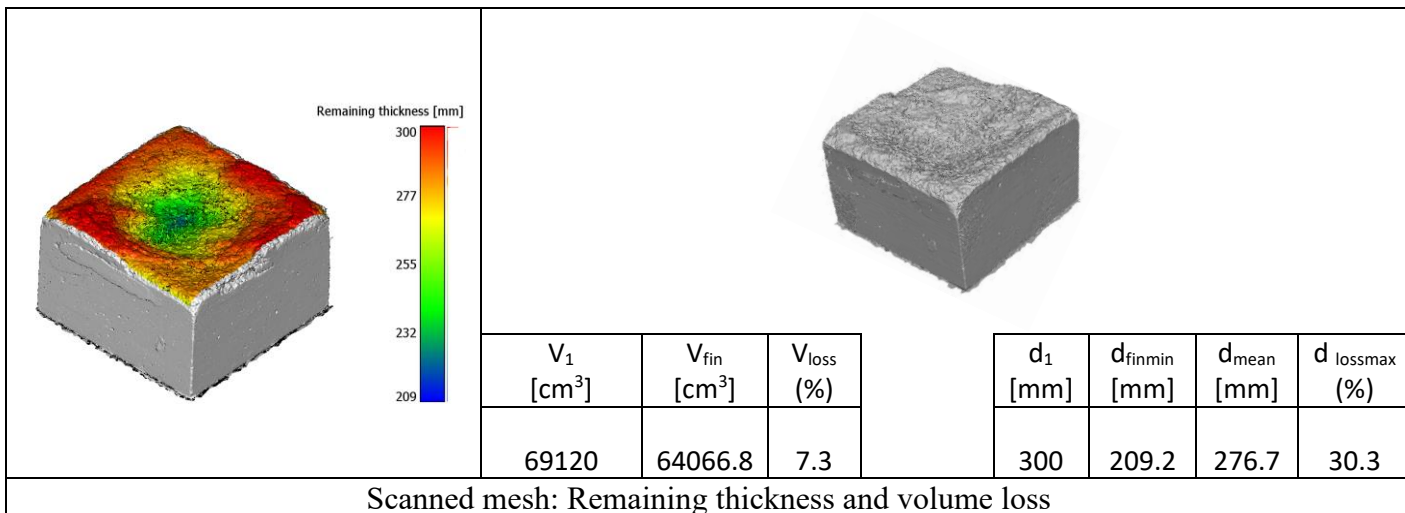
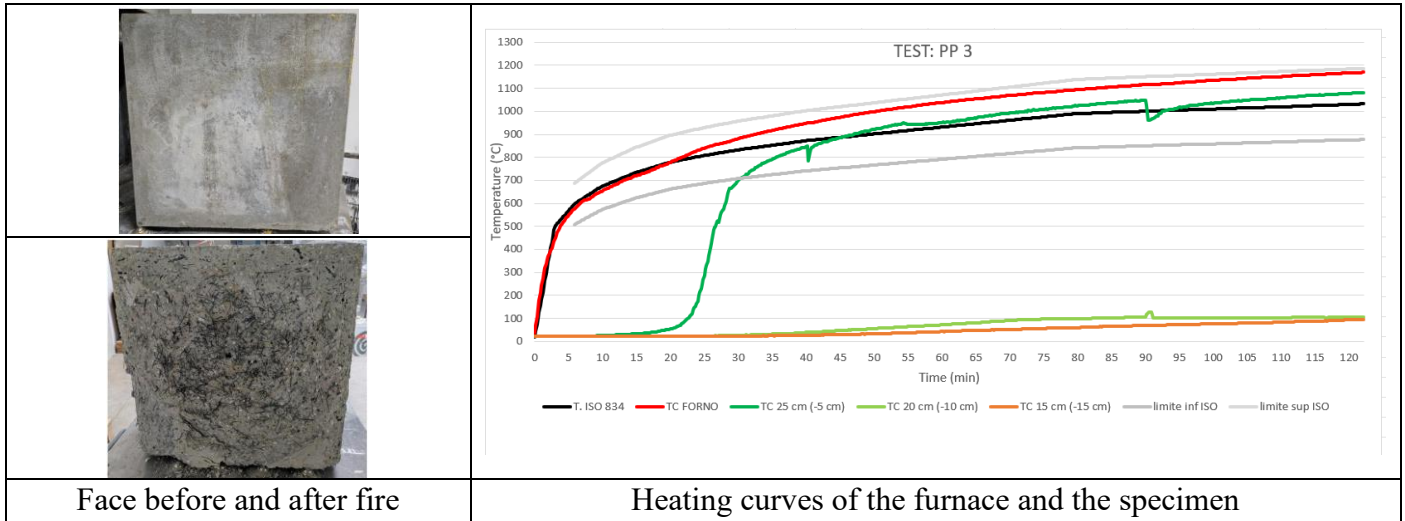
Extracted core : 2 (further to fire exposed face)

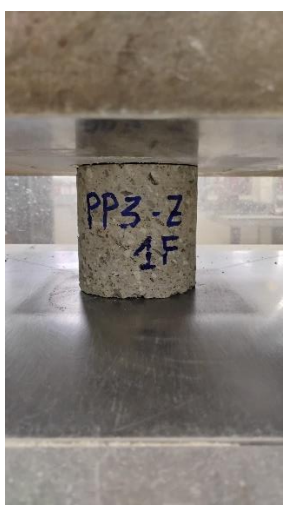
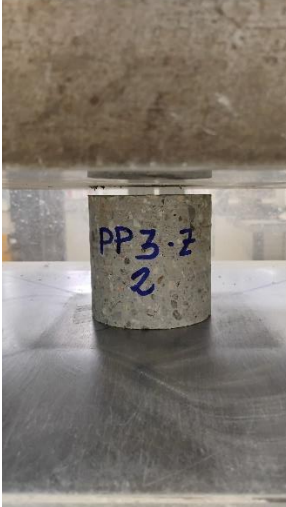
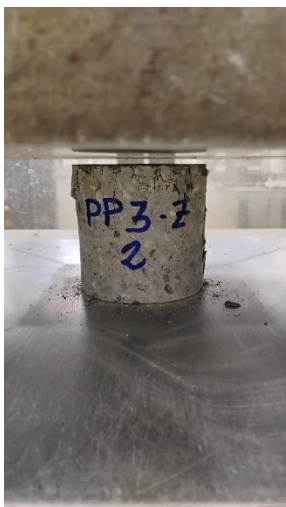
Test: PP 2



			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	fc (MPa)	Density(kg/m ³)	F c (MPa)
2238	23.8	2342	81.1
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	

Test: PP 3



			
Before comp. test	After comp. test	Before comp. test	After comp. test
Density (kg/m ³)	fc (MPa)	Density(kg/m ³)	F c (MPa)
2245	19	2350	69.5
Extracted core: 1F (near to fire exposed face)		Extracted core : 2 (further to fire exposed face)	